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Follows

PUTTING DOWN AND DEVELOPING WELLS FOR IRRIGATION

By

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Irrigation Engineer, Division of Irrigation
Soil Conservation Service

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By CARL ROHWER, *irrigation engineer, Division of Irrigation, Soil Conservation Service*

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INTRODUCTION

The quantity of water available from streams and reservoirs in the arid regions of the West is frequently insufficient to supply the needs of the land suitable for irrigation. Where this condition exists, additional sources of water must be sought. In many areas large quantities of water are stored beneath the surface of the ground in layers of saturated sand and gravel. Not all of this water can be

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recovered, nor is the water table in all areas close enough to the surface to be within the economic limit of recovery, but where conditions are favorable, the water stored in the soil may be used as the source of an additional supply for irrigation.

The most feasible method of recovering this water is by pumping from wells, and for this purpose wells capable of supplying large quantities of water at a reasonable cost are required. Wells of this type differ materially from those used for domestic purposes, and for this reason farmers, well drillers, and others who are concerned with the construction of pumping plants for irrigation, should be familiar with all the factors necessary to obtain a satisfactory well.

FACTORS AFFECTING THE FEASIBILITY OF PUMPING PLANTS

The construction and operation of a well and pumping plant for irrigation are expensive undertakings. Before a project of this sort is undertaken a careful investigation should be made of the possibilities of success. The principal items to be considered are the legal status of irrigation from wells, the quantity of water required for the crops to be irrigated, the quantity and quality of water available from the underground source, and the economic limit of pumping lift. In addition a satisfactory well contract should be drawn, the land must be prepared for irrigation, the soil must be suitable for growing the proposed crops under irrigation, the climate must be favorable, accessible markets must be at hand, and facilities for financing the undertaking must be available. Some of these subjects are explained in detail in other publications of the United States Department of Agriculture (*8*, *9*, *10*, *11*, *12*, *13*, *14*, *15*, *16*, *18*, *23*, *24*, *26*, *34*, *39*),[2] but the essential information is given here for those who do not have access to them.

LEGAL STATUS OF PUMPING FROM WELLS

Only a few States have clearly defined laws relating to pumping from wells for irrigation (*6*, *33*), but nevertheless the right to pump water should be safeguarded by compliance with all the legal requirements. The procedure to be followed in order to establish a right to pump from wells should be determined by writing to the official in charge of irrigation in the State, and operations should be carried out in conformance with any existing restrictions as to sanitary measures or to tapping artesian formations. Where the doctrine of appropriation is in force, the well owner is protected against reduction in the water supply of his well caused by a well or wells being drilled near him at a later date. Where, however, the doctrine of correlative use has been adopted, every landowner has a common right to use the underground water in proportion to the needs of his land. Where the latter doctrine is in force, there is always the possibility that wells drilled subsequently will cause a permanent lowering of the groundwater level. In States where no definite policy has been adopted there is danger of overdevelopment in the use of underground water.

[2] Italic numbers in parentheses refer to Literature Cited, p. 83.

WATER SUPPLY

QUANTITY

The water required to irrigate various crops depends on the crop, the type and fertility of the soil, the topography, the climate, and the method of irrigation. In irrigated areas the quantity of water required can be determined from the local practice and in newly developed areas it can be approximated from the depth of water used under similar conditions elsewhere or from the information given in the publications of the Department (*12*, *14*, *15*, *16*) on irrigation requirements of arid and semiarid lands. The tables in these bulletins give the net irrigation requirements exclusive of rainfall for the principal irrigated areas in the West and also the percentage of the total requirement which is used each month. These tables show that June and July are usually the months of maximum demand, and that during these months from 3 to 9 inches of water is used, or from 20 to 40 percent of the total seasonal requirement. In general, areas having a long growing season have the minimum peak demand and those having a short growing season have the maximum peak demand.

The values given in the before-mentioned publications are for average conditions. If there are unusual features, such as growing only one crop, growing two crops simultaneously on the same area, or if the soil is very sandy, then the rate of maximum demand would probably be greater.

The capacity of the well and pumping plant should be great enough to supply all the water required during the month of maximum demand. Large pumping plants require less time to supply the required quantity of water, and consequently the labor cost for irrigating is smaller, but large pumping plants cost more to build and operate than small ones. It has been found that the most economical results are obtained, particularly for electric-motor-driven plants, with the smallest plant that will supply the required quantity of water during the period of maximum demand even though the labor cost of applying the water may be slightly higher (*4*).

For general farm crops about 300 gallons per minute is the smallest flow that can be economically handled, and where the yield of the well is less than this amount it is doubtful whether a pumping plant will be successful except for small tracts, such as orchards or gardens, where the furrow or the sprinkler system can be used to apply the water. In some sections of California, Arizona, and Nevada, however, 300 gallons per minute would be considered a good flow. In cases where it is not possible to get a sufficient supply of water from a single well, it is often possible to obtain the desired amount by using a battery of wells (p. 16) or several separate wells.

Pumping plants are frequently built to provide a supplemental supply of water, and during periods of drought large numbers of plants of this type are constructed. In case the plant is being designed to provide a supplemental supply, the quantity of water necessary will be the difference between the total requirement and the amount supplied by rainfall.

In some sections the supply of ground water is sufficient to provide whatever quantity is needed for irrigation, but in many areas condi-

tions are not so favorable. In these regions the capacity of the well will determine the size of the plant; the acreage irrigated and the kind of crops grown will have to be adjusted to the capacity of the well.

It is impossible to predict whether a well will be satisfactory or not, but in some areas conditions are more favorable for locating a good well than in others. The best wells are usually found where the water-bearing formation is of considerable thickness and is made up of fairly coarse material free from very fine sand, clay, or cementing material. The ground water should be at a relatively shallow depth and should be fed from a dependable source. The most favorable locations for good wells are in the valleys adjacent to streams and on the alluvial cones where streams from mountain areas flow out on the plains. Where irrigated areas are underlain by sand or gravel, the conditions are generally favorable for getting good wells.

When there is doubt as to the possibility of getting a good well, test holes should be put down to locate the water-bearing formation and determine the character of the water-bearing material. (See pp. 18–23 for methods of drilling test wells.) A careful record should be kept of the depth to water and the location and thickness of the various materials penetrated by the test hole. Samples of the water-bearing material should be saved. From the log of the test hole and the samples of the water-bearing material, it is possible to determine within reasonable limits whether a satisfactory well can be drilled at a given point. If the conditions are found to be unfavorable for a good well at the first test hole, a new location should be chosen and tested. Several test holes should be drilled before abandoning the hope of finding conditions suitable for locating a satisfactory well. When possible the well should be located so that the greatest area of the farm can be irrigated from the well. A topographic map of the farm will be very useful in laying out the irrigation system.

QUALITY

The ground water in most arid regions contains some alkali, and in a few places the concentration is so great that the water is injurious to plants and sometimes to the soil also. Some ground water contains chemicals that corrode metal casing, and some contain sufficient gas in solution to interfere with the operation of pumps. If there is doubt as to the quality of the water, a sample should be sent to the State agricultural college or other qualified agency for testing.

PUMPING LIFT

The limit of the lift against which water may be profitably pumped for irrigation varies with the cost of pumping and the value of the crops grown. As greater care is being used in the design of pumping plants and as the efficiency of pumps is being constantly increased and the cost of power reduced, the cost of pumping an acre-foot of water per foot of lift has been correspondingly reduced. High lifts are also feasible if the water pumped is to be used only as a supplemental supply in case of shortage. Low-priced agricultural products and small yields, however, reduce the economical pumping lift.

The average lift through which water was being pumped in 1930 for irrigation in each of the Western States from all sources including streams and lakes is given in table 1 together with the estimated economic limit of pumping lift from wells. The area irrigated by pumping in each State, the cost of the pumping plant per acre irrigated, and the cost of operation are given also. The average lift shown is less than the estimated economic limit of lift, and although it is possible to operate a pumping plant successfully under favorable conditions against lifts equal to the limiting values, anyone contemplating the installation of a pumping plant should not plan to exceed the average lift given in the table unless he is favorably located as to markets or can grow special crops from which the cash returns are higher than from general crops. Especially fertile soil and a favorable climate make it possible to pump successfully against high lifts. The cost of power for pumping is almost directly proportional to the lift. For this reason the chances of financial success should be considered carefully before going into any project where the lift against which the pump must operate is above the average values given.

TABLE 1.—*Area irrigated, investment in plants, cost of operation, and average lift of all irrigation pumping plants in 1930 and estimated economic limit of lift for irrigation for wells* [1] [2]

State	Area irrigated by pumping	Investment in pumping plant per acre [3]	Cost of operation per acre [4]	Average lift [5]	Estimated economic limit of lift [6]
	Acres	*Dollars*	*Dollars*	*Feet*	*Feet*
Arizona	104, 637	58. 70	10. 76	46	40 to 50
California	1, 453, 272	146. 04	10. 05	53	[7] 50 to 100
Colorado	12, 143	30. 66	5. 36	25	40
Idaho	3, 546	19. 64	2. 30	32	35 to 40
Kansas	11, 648	33. 44	3. 69	26	50
Nebraska	23, 452	19. 95	4. 03	29	50
Nevada	2, 117	20. 19	4. 82	31	30 to 40
New Mexico	30, 425	38. 75	6. 44	40	40 to 50
Oregon	3, 804	59. 07	10. 72	27	30 to 100
Texas	60, 793	47. 15	8. 50	55	60 to 100
Utah	10, 283	34. 64	3. 58	36	50 to 75
Washington	19, 456	82. 24	15. 43	59	50 to 80

[1] Data in the first 4 columns of figures were taken from the United States census of 1930 (*38*).
[2] The first 3 columns represent plants pumping exclusively from wells.
[3] Data may include other investment besides that in well and pumping equipment.
[4] Covers cost of power, attendance, and repairs.
[5] Covers all pumping whether from wells, streams, or reservoirs.
[6] Estimates based on information gathered from members of the Division of Irrigation and other sources.
[7] Under special conditions economic limit of lift may exceed 500 feet in California.

Where the pumping plant is being installed to supplement the supply of water for irrigation from some other source, the feasibility of the project depends primarily on finding a satisfactory supply of ground water at a reasonable depth, because the land is already in shape for applying water, the suitability of the soil and the climate for growing crops under irrigation are known, and the market for the crops is established. If, however, the well is located in an area where irrigation has not been practiced previously, each of these items must be considered. It would be desirable also to study what is being done in similar areas elsewhere and to find out from the county agricultural agent or State experiment station whether they consider the project feasible.

WELL CONTRACT

If, after a thorough investigation, it is found that conditions are favorable for the construction, financing, and successful operation of a pumping plant for irrigation from wells, the next thing to be considered is the drilling of the well. Except under very favorable conditions the landowner or farmer will not be able to do this work himself. He should get in touch with a reliable well driller and should discuss with him what work is to be done and what the cost is to be. When drilling deep and expensive wells the agreement in regard to these matters should be put in writing in the form of a well contract. With small wells, however, an oral agreement may be sufficient.

The well contract should specify the work to be done, the time of starting and completing the work, the equipment to be used, and the bid price for the various items. If the landowner is to supply any of the equipment, materials, or labor, each item should be included in the contract. If reconditioned casing is to be used in the well, this fact should be designated in the contract. The driller should be required to furnish a bond to guarantee satisfactory completion of the well, carry liability insurance to protect himself in case of property damage, and compensation insurance sufficient to cover his liability under the workman's compensation act. The principal items concerning the well that should be included in the contract are the length, diameter, and thickness of the starter, if used; the type, material, and dimensions of the shoe; the length, diameter, and thickness of the casing; the material of which the casing is to be made, the size and spacing of the reinforcing bands when large single-thickness casing is used; the size and number of the perforations and the method of perforating; the thickness of the gravel envelope, if used, and the size of the gravel; and the method of developing and testing the well. If concrete casing is to be installed the mix of the concrete should be designated. A guaranteed minimum payment to the driller should be specified in the contract in order to protect the driller, and the maximum depth of well, or a provision authorizing the owner to stop the work when he considers the well deep enough, should be included in order to protect the owner. A clause should be included in the contract to the effect that the bore of the well must be straight enough to permit the insertion and successful operation of the type and size of pump to be used. If any changes in plans become necessary after the work has started, the order for the change should be in writing.

In some sections it is the custom for the well driller to contract to drill a well of specified capacity. If many wells have been drilled in the region and the water-bearing formation is known to be uniformly productive, this plan may be feasible, but it is obvious that under these circumstances the driller takes all the risk, and must bid enough higher to protect himself. The maximum acceptable draw-down when pumping the specified amount and the number of hours the well should be pumped at this rate should be designated in the contract. If the draw-down is not specified, the required quantity may be obtained by drawing down the well below the economical limit, and if the time is not specified the well may not hold this capacity when pumped a longer time. These contracts should also have a clause providing a penalty if the well does not meet the terms of the contract and a bonus if the

well exceeds the terms. The penalty or bonus should be computed on the basis of a unit amount for a definite number of gallons of excess or deficiency. The penalty and bonus clause may be included in other forms of well contract to advantage because it provides an incentive for the driller to do better work.

When the well is completed, the driller should be required to furnish a complete log of the well showing the depth of water, the location, character, and thickness of the different materials encountered in the well, the location of the points where the diameter of the casing was changed and of the perforations in the well. This information will be invaluable if at some later date it becomes desirable to reperforate the well or lower the bowls of the pump.

In case any controversies arise the procedure to be followed in settling the dispute should be set forth in the contract. Large well-drilling companies have their own contract forms, and in case they are used the landowner should read over their provisions carefully before signing so that he will understand the agreement. Forms for well-drilling contracts have been prepared which protect both the driller and the landowner. Information concerning these contracts can be obtained by writing to the Division of Irrigation, Soil Conservation Service, Berkeley, Calif.

FACTORS AFFECTING FLOW OF GROUND WATER INTO WELLS

The source of supply for irrigation wells is the water that accumulates in the surface layers of the earth as the result of the percolation of water from rain and snow, the percolation of water applied for irrigation or spread to increase the ground-water supply, and the seepage of water from streams, canals, and reservoirs. All the water that sinks into the soil from these sources is not available for pumping; some of it is evaporated from the surface of the ground while it is still damp; some of it is brought back to the ground surface by capillary action and then evaporated; some of it is held in the soil as capillary and hygroscopic water; and some of it is taken up by the roots of growing plants to be evaporated from the surface of the leaves. The remaining water moves downward until it reaches a zone of saturation or comes in contact with a layer of impervious material such as clay or shale. At this point the water starts to spread laterally filling up the pores of the material in its path as it spreads.

These processes have continued for long periods of time and, as a result, have built up a supply of water which underlies large areas of the land surface of the earth. The water, with the exception of that held in closed basins, is all moving toward points where it can escape into a spring, stream, or swamp. In most areas additions to the water supply about equal the amount being lost, resulting in a condition of approximate equilibrium. In some places, however, the balance has been artificially interfered with as in the case of irrigated areas. Here the water level may still be rising on account of the application of irrigation water or may be lowering on account of excessive pumping.

The water that exists in the zone of saturation is known as ground water, and the upper surface of the zone of saturation, or the free-

water surface, is known as the water table. When the water in the zone of saturation is confined between layers of impervious material the water in contact with the top layer of impervious material is under pressure and consequently there is no water table. When a zone of saturation of this type is tapped the water will rise above the level of the bottom of the confining layer. This condition produces what are known as artesian basins. Where the ground water is not under pressure, as in the case where the zone of saturation is not confined between layers of impervious material, the water when tapped will not rise above the level of the water table. Regions where this condition exists are known as nonartesian or normal-pressure areas. The conditions that give rise to the two types of areas are shown in figure 1 which represents a section of a broad valley.

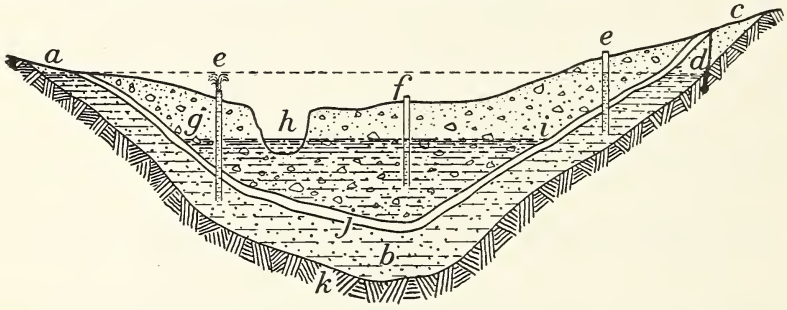

FIGURE 1.—Cross section of a valley containing artesian and nonartesian water-bearing formations: *abc*, An artesian stratum; zone between water table *gi* and impervious stratum *j* is a nonartesian formation; *d*, upper level of artesian stratum; *e*, artesian wells; *f*, an ordinary well; *h*, a stream; *k*, a layer of impervious rock.

The quantity of water in a layer of saturated material or aquifer depends on the thickness and extent of the layer and the porosity of the material composing it. Porosity is the ratio of the volume of the openings or pores in the material to its total volume and is usually expressed as a percentage. Porosity increases with the fineness of the material and with the sharpness of the soil particles, and is greatest when all the particles are of uniform size. When the particles are well graded in size, the smaller ones fill the spaces between the larger ones, and, if the sizes of the different particles are in the proper proportion, each smaller size will just fill the spaces between the larger particles. The porosity of soils varies widely, ranging from as low as 20 percent for graded sand to as high as 65 for very heavy clay. Water-bearing formations suitable for providing water for irrigation wells usually have porosities ranging from 20 to 40 percent of the total volume of the material.

From the foregoing it is seen that clays have the largest percentage of pore space although it is a well-known fact that wells in clay yield very little water. The reason that these wells are not satisfactory even though the clay contains much more water than sand or gravel is that the clay will not give up the water when the well is pumped. Clay is made up of extremely fine particles, and, as a result, the pore spaces also are extremely small and hold water against the force of

gravity by capillarity. The water so held is known as capillary water. In addition a portion of the water, known as hygroscopic water, is held by molecular attraction. Neither capillary water nor hygroscopic water is given up when a well is pumped. The moisture held in this manner is called the specific retention. It is the ratio of the amount of water retained to the volume of the water-bearing material expressed as a percentage, and may amount to from 5 to 35 percent (*25, pp. 57–59*) of the volume of the water-bearing material depending on the distance from free water and the nature of the water-bearing medium. The lowest percentages are retained by sand and gravel and the highest by clay and clay loam. The percentage of the moisture retained decreases in general as the distance from the free-water surface increases (*22*).

The quantity of water that a definite volume of water-bearing material will yield as distinguished from that which it will retain is called the specific yield. It is expressed as a percentage and is the ratio of the yield from a given volume of water-bearing material to the volume of the material. The specific yield varies between 16 and 41 percent (*7, pp. 121–123*) of the volume of the water-bearing medium. It is greatest for sand and gravel and least for clay and clay loam. It has been estimated by Lee (*7, p. 154*) that from 15 to 30 percent of the volume of the water-bearing medium represents the water that is available for pumping although actual tests have shown as low as 12 percent (*3, pp. 82–87*) to be all that could be obtained.

As previously explained, ground water is not static except in closed basins. It has a definite, though slow, velocity which depends on the slope of the water surface, the size, shape, uniformity, and compactness of the particles in the medium through which the water is moving, and the temperature of the water. The effect of temperature, although large, is usually disregarded because the temperature of the ground water does not vary through wide limits. The rate of movement of water through the pores in saturated soil at all velocities below the critical is directly proportional to the slope of the water table. This relation is known as Darcy's law. The effect of the other factors on the rate of flow is so complicated that it cannot be expressed by a simple law, but it can be determined experimentally.

The combined effect of these factors is expressed by what is known as the transmission constant (*19, pp. 200–203*) or the coefficient of permeability which is the rate at which water will flow through a column of the material of unit section when the slope is unity, or, in other words, when the head is equal to the length of the column of material. The coefficient of permeability is given in gallons per day, and the transmission constant in cubic feet per minute (*35, p. 148*). Formulas have been derived for computing these constants, but the results obtained have not been satisfactory (*32, p. 127*). The constants computed from the analyses of the materials have usally been too low (*35, p. 150*). More satisfactory results are obtained when these constants are determined experimentally by observing the rate at which water percolates through the material. The other factors required to compute the quantity of flow are obtained by direct observation. The slope of the water table is found from observations on wells, and the depth and extent of the water-bearing medium are obtained by putting down test holes. The product of the area of the

water-bearing layer at right angles to direction of flow, the slope of the water surface, and the transmission constant or the coefficient of permeability gives the quantity of water flowing through the section in cubic feet per minute or in gallons per day.

The velocity of flow may also be measured by noting the time it takes a salt solution to move from one well to another in the directions of flow of the ground water (*31, pp. 16–85*). The salt is introduced in the upper well, and the time of arrival of the solution at the lower well is determined by chemical analyses or by electrical methods. Observations have been made by this method on the velocity of flow of ground water in many sections of the United States. These studies show that the velocity varies from a fraction of a foot to nearly 500 feet per day depending on the slope and the characteristics of the water-bearing material. The ordinary range of velocities, however, is from 1 to 100 feet per day.

The volume of ground water in storage in a given area may be determined from the area and depth of the saturated zone and the porosity of the water-bearing medium. However, the volume of water that may be withdrawn for use for irrigation or other purposes at any time from a given area by lowering the water table a definite amount, depends on the specific yield of the water-bearing medium rather than the porosity because, as previously explained, much of the water in the zone of saturation is held so firmly in the soil that it cannot be drawn out by pumping.

The water that may be safely withdrawn each year depends on the recharge, that is, the rate at which water is being added to the zone of saturation by inflow from other areas, by downward percolation of the moisture from rain and snow falling on the area, by the penetration of water applied in irrigation or spread to increase the water supply down to the zone of saturation, by seepage from streams, or by the combination of any of these sources of supply. In an emergency, such as a drought, water may be withdrawn at a faster rate than it is supplied, but in the long run the rate of withdrawal cannot exceed the rate of recharge or the water table will continue to lower. The disastrous effects of this practice have already been observed in some areas.

The rate at which water may be safely withdrawn from a given area can be determined approximately, but it is a difficult problem because there are so many factors that have to be estimated. The rainfall and the amount of run-off can be measured, but no one can say definitely how much of the water that seeps into the soil will be used by plants or lost by evaporation. The same may be said of the water that is applied in irrigation. Furthermore, the inflow from other areas, which is frequently an important source of supply, is difficult to measure accurately on account of the fact that the velocity of the water in the water-bearing medium cannot be measured accurately nor can the pore space through which the water is moving be determined with certainty. Where pumping is being practiced, the simplest method of getting information as to the rate at which water may safely be withdrawn from a given area is to measure the lowering of the water table in the wells from time to time.

If there is a gradual lowering of the water table extending over a period of years, then the rate at which the water is being pumped is exceeding the rate of recharge, and the lowering of the water table will continue unless the rate of withdrawal is reduced or the rate of recharge is increased. During periods of drought the rate of recharge decreases, and as pumping is usually heavier because of the drought the combination produces a marked lowering of the water table which might be interpreted as indicating a definite overdraft on the area. However, a period of wet years increases the rate of recharge and usually reduces the pumping draft. This condition again establishes the balance between the rate of withdrawal and recharge unless the area is being pumped at too high a rate.

HYDRAULICS OF WELLS

When an irrigation well is put down into a layer of water-bearing material and pumped, the water in the casing is first lowered, and the water from the saturated material surrounding the casing flows into the well. If pumping is continued the water in the well will continue to lower, and the water coming from the saturated material will increase until it will just equal the discharge. The water moving toward the well has to pass through the pores in the sand, and the closer it gets to the well the faster it has to move because the area through which it has to travel is continuously decreasing.

As previously explained, the velocity of water flowing through a water-bearing medium is directly proportional to the slope of the water surface. For this reason the slope increases as the water approaches the well, and the change in the slope is directly proportional to the change in the velocity. The water surface formed, as the result of the continuously increasing downward slope toward the well is an inverted bell-shaped depression which is known as the cone of depression. The circle formed by the intersection of the outer edge of the cone of depression with the static water surface is called the circle of influence, and the area of this circle is called the area of influence. The intersection of the surface of the water in the cone of depression with a vertical plane through the center of the well is a curved line, known as the draw-down curve. The distance that the water level is lowered by pumping is the draw-down. It is the distance between the water level in the well when being pumped and the static water level or water table. These different features of a well are shown in figure 2 which is a vertical cross section of a typical well in a nonartesian formation.

The flow into a well depends on the draw-down, the thickness and nature of the water-bearing stratum, the diameter of the well and the radius of the circle of influence. Formulas (*21*, *37*) have been developed showing the relationship between these factors and the discharge for various types of wells, but owing to the complexity of the phenomena involved and the difficulty of determining accurately the values of some of the variables, discharges computed by these formulas have not been satisfactory. These formulas, however, show certain fundamental relations that are of value in studying wells.

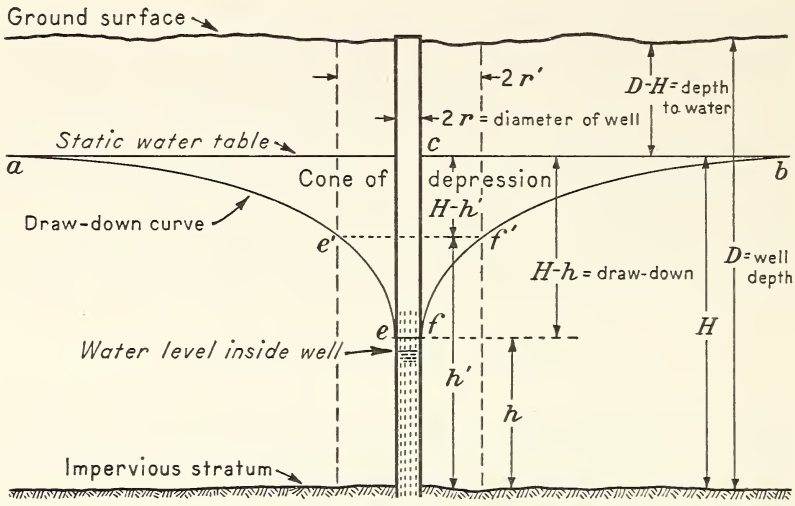

FIGURE 2.—Vertical cross section of a typical irrigation well in a nonartesian formation. (Not to scale.)

For the type of well shown in figure 2 the discharge formula is (*37, pp. 278–286*)

$$Q=K'\frac{H^2-h^2}{\log\frac{R}{r}},$$

in which Q=discharge in gallons per day.

K'=a quantity which depends on the characteristics of the water-bearing material.
H=distance of static water level above bottom of water-bearing formation in feet.
h=distance of water in well above bottom of water-bearing formation in feet while being pumped.
R=radius of circle of influence in feet.
r=radius of well in feet.

For an artesian well which penetrates the entire depth of a water-bearing formation the discharge formula is

$$Q=2K'\frac{H-h}{t\log\frac{R}{r}},$$

in which t is the thickness of the water-bearing formation, and the other letters have the same significance as before.

If two wells of different diameters are in the same formation and the draw-down is kept the same, then the relation of the discharges of the two wells will be

$$\frac{Q}{Q'}=\frac{\log\frac{R'}{r'}}{\log\frac{R}{r}}.$$

This relation holds for both types of wells.
The formula

$$Q=K'\frac{H^2-h^2}{\log\frac{R}{r}},$$

which is for nonartesian wells, may be written

$$Q=K'\frac{(H+h)(H-h)}{\log\frac{R}{r}}.$$

If the draw-down is small, then $H+h$ is approximately equal to $2H$, then

$$Q=2K'\frac{H(H-h)}{\log\frac{R}{r}}$$

This formula shows that in wells of this type the discharge is proportional to the quantity K', the depth of water H, the draw-down $H-h$ and

$$\frac{1}{\log\frac{R}{r}}.$$

The formula for the artesian well shows that the discharge is proportional to the quantity K', the thickness of the artesian formation t, the draw-down $H-h$ and

$$\frac{1}{\log\frac{R}{r}}.$$

All the formulas show that the discharge from a well is directly proportional to the transmission constant of the material in the water-bearing stratum. As previously explained, the value of the transmission constant increases as the coarseness and porosity of the water-bearing material increases and decreases as the compactness increases. It is also affected by the uniformity of the material. The transmission constant varies through wide ranges, the value for coarse sand being 4,000 times as great as that for fine sand (*37, p. 280*). An artesian water-bearing formation in Utah was found to be 100,000 times as permeable as the overlying clay (*20, p. 23*). It is important, therefore, to have as coarse a water-bearing medium as possible and also free from fine material such as silt or clay because it is the fine material that fills the pores between the large particles and retards the flow of water.

It is frequently assumed that the water-bearing medium is satisfactory simply because it contains a good many boulders the size of baseballs or larger. If there were no fine particles, these boulders would be an indication of an excellent well. Usually, however, the spaces around these boulders are completely filled with graded sand, and the result is that the boulders obstruct the flow. This is clearly

shown in figure 3, which is a section of such material taken at right angles to the direction of flow of water. It is obvious that the water cannot flow through the large rocks, and consequently is retarded more than it would be if all the space were filled by the smaller particles.

In wells, where the casing penetrates the full depth of the water-bearing stratum, the capacity of the well is directly proportional to the thickness of this stratum if the draw-down and other conditions remain the same. It may also be said that the deeper the well is driven into a water-bearing stratum the greater will be the discharge for a given draw-down. This fact is frequently lost sight of when wells are being put down. Where the water-bearing formations are thick there is a tendency to limit the depth of wells on account of the cost. It is true that increasing the depth increases the cost of construction, but this additional cost is usually balanced by the saving in cost of operation resulting from the decreased draw-down.

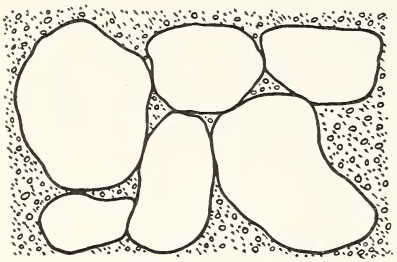

FIGURE 3.—Cross section of water-bearing formations made up of boulders and fine sand.

In wells which penetrate deep into water-bearing formations of considerable thickness, the capacity is directly proportional to the draw-down so long as the draw-down is small in comparison with the depth of water in the well. If the draw-down is large, then the discharge of the well does not grow larger as rapidly as the draw-down increases. If the depth of water in the well is small the yield per foot of draw-down will decrease as the draw-down increases. The decrease in yield is caused by the fact that as the draw-down increases the depth of sand through which the water enters the well is decreased. In other words, the effect of the increased draw-down is counteracted by the effect of the decreased depth of water-bearing sand through which the water can enter the well. In artesian wells the yield is directly proportional to the draw-down as long as the draw-down is less than the artesian pressure.

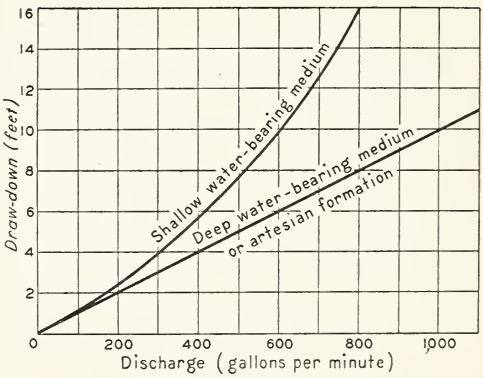

FIGURE 4.—Discharge-draw-down relation of a well in a thin water-bearing formation and one in a thick water-bearing formation or in an artesian stratum.

The relation of the discharge to the draw-down for the different conditions is shown in figure 4. The discharge from the well in the shallow water-bearing medium increases 80 gallons per minute when

the draw-down is increased from 2 feet to 3 feet, whereas, it increases only 40 gallons per minute when the draw-down is increased from 10 to 11 feet. It is apparent from these values that when the limit of the draw-down is being approached, the increase in yield is obtained at the expense of a disproportionate increase in the draw-down. This fact should be kept in mind when deciding how much water to pump from a well. For the same conditions in the artesian well or the well drilled deep into a thick water-bearing formation, the increase in discharge is 100 gallons per minute whether the draw-down is increased from 2 feet to 3 feet or from 8 feet to 9 feet. In this case the yield may be increased without causing a disproportionate increase in the draw-down.

Consideration of the theoretical relation of the various factors affecting the discharge from wells leads to the conclusion that the discharge increases as the diameter increases but not in the same proportion.[3] Theoretically, the discharge from a 2-foot well, assuming that the radius of influence is 1,000 feet and that the draw-down is constant, is only 10 percent greater than that from a 1-foot well, and the discharge from a 4-foot well is only 21 percent greater than that from a 1-foot well. (*27, p. 264.*) For other conditions the percentages would be different. Experiments made on two wells in Colorado under practically identical conditions showed, however, that the discharge from the 2-foot well was 25 percent greater than that from the 1-foot well (*5*). If, while the diameter is increased the discharge is kept constant, then the draw-down will decrease in about the same ratio as the discharge increases when the draw-down is constant. The theoretical change in the draw-down caused by increasing the diameter of the well is shown graphically in figure 2 (*17, p. 24*). When the diameter of the well is increased from $2r$ to $2r'$, the level of the water in the well changes from ef to $e'f'$, if the loss of head caused by the resistance of the casing to the flow of the water through it is neglected. The draw-down is reduced from $H-h$ to $H-h'$. There is some doubt, however, whether the draw-down curve for the large well coincides with the curve for the small well as shown in figure 2.

From the foregoing discussion it is seen that doubling the diameter of the 1-foot well increases the discharge of the well somewhere between 10 and 25 percent, whereas, doubling the depth of penetration of the well into the water-bearing medium increases the discharge by approximately 100 percent. If the discharge were kept constant, the draw-down would be cut in half. This fact should be given careful consideration when putting down a well.

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[3] Q is inversely proportional to $\log \frac{R}{r}$, (37, p. 283), hence

$$\frac{Q}{Q'}=\frac{\log \frac{R'}{r'}}{\log \frac{R}{r}}$$

If it is assumed that the radius of influence R will not change materially with small changes in Q, R' may be replaced by R and the formula then becomes

$$\frac{Q}{Q'}=\frac{\log \frac{R}{r'}}{\log \frac{R}{r}}$$

from which the value of $\frac{Q}{Q'}$ may be computed for any assumed value or R, r, and r'. This relation holds for both artesian and nonartesian wells.

BATTERY WELLS

In many areas the thickness of water-bearing material is small. It is impossible to increase the capacity of the well by deepening because wells in these areas are usually drilled through the water-bearing formation. Where additional capacity or a smaller draw-down for a given capacity is desired a battery of wells is installed. This is a group of wells arranged in a line or in a circle and connected either by siphons to a central well in which the pump is installed or by a suction header to the pump which is located in a pit at a central point. When the latter arrangement is used, the drop pipe for each well is attached to the suction line, but when siphons are used they discharge into the central well which has to be large enough to accommodate the drop pipes of the siphons as well as the suction pipe of the pump. For this reason the central well is usually made larger in diameter than the other wells. When a suction header is employed all the wells are usually made the same diameter. The wells in battery systems are made smaller in diameter than when single wells are used except, of course, the central well in siphon systems.

The battery system is particularly adapted to conditions where the water table is relatively close to the ground surface because the suction header or the siphon pipes have to be close enough to the water surface so that the draw-down in the wells will not cause the suction limit to be exceeded.[4] If the water table is at a considerable distance below the ground surface, tunnels or very deep trenches will be necessary. The construction cost under these conditions is likely to be prohibitive.

The method of locating the wells on the circumference of a circle is best suited to conditions where the water-bearing medium contains clay or considerable fine sand which does not give up water readily. The effect of this arrangement is equivalent to that of having one large well. This is clearly shown in figure 5 which is a vertical section through a battery of wells. The position of the water surface is at *ef* if all the water is pumped from a single well, and *aefb* is the draw-down curve. The level of the water is at *e′ f′* when the same amount of water is being pumped from the battery of wells. The intersection of the line *e′ f′* with the draw-down curve *aefb* at *e″ f″* locates two points which determine the radius *Re* of the single well which is the equivalent of the battery of wells with the radius *Ra* because the draw-down of this well is the same as that of the battery of wells (*17*, *p. 20*).

Satisfactory results have been obtained by putting down four small wells in the bottom of a pit 10 feet in diameter, but in general better results will be obtained if the diameter of the circle is made considerably larger, probably from 50 to 100 feet would be about right for most conditions. From four to seven wells, depending on the diameter of the circle, are all that are necessary in the battery. If they are spaced closer together there will be considerable interference between wells (p. 17).

[4] The practical limit of suction lift for pumps is 22 feet at sea level, 17 feet at 5,000 feet elevation, and 14 feet at 10,000 feet elevation. Siphons will operate if these lifts are exceeded, but they will probably require frequent priming on account of the accumulation of air from the water or from small leaks in the pipe.

The method of placing the wells of the battery in a line is satisfactory whether the water-bearing stratum is fine sand or coarse gravel. This arrangement is used most when the ground water has a definite movement in one direction, and in this case the wells are placed in a line at right angles to the direction of flow of the water. By this method a large portion of the flow through a given section may be intercepted.

The spacing of the wells in a battery arranged in a line will depend on the diameter and depth of the individual wells and the nature of the water-bearing medium. On account of their cost deep wells are spaced at greater intervals than shallow wells, and wells

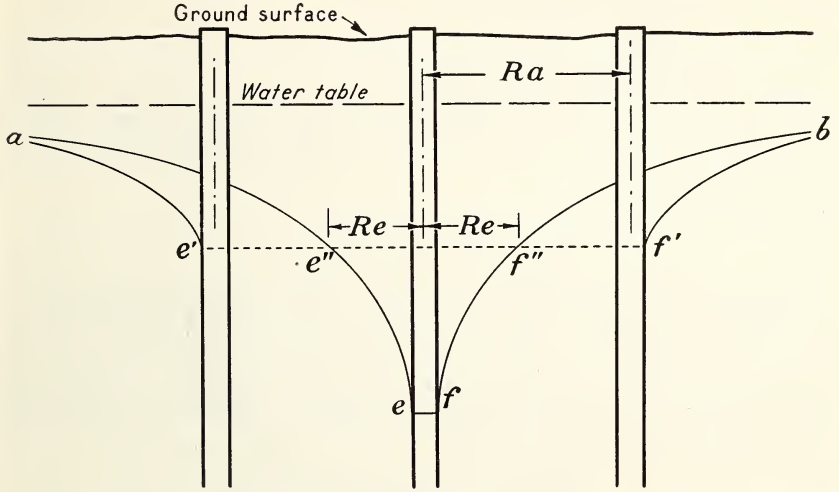

FIGURE 5.—Draw-down curves of a single well and of a battery of wells. (Not to scale.)

in tight materials are placed closer together than those in open formations. Small-diameter wells are placed closer together than large wells. For shallow wells of the type used for irrigation the spacing should be from 30 to 75 feet (*5*).

The interference of the wells with each other will be less when the greater spacing is used, but the cost of installing the equipment will be greater on account of longer connecting pipe lines and trenches.

INTERFERENCE OF WELLS

The amount of interference between wells in a battery depends on the diameter, depth, spacing, and number of the wells, the draw-down and the nature of the water-bearing material. This subject has been investigated theoretically by Slichter (*30*), and has been studied experimentally in Kansas,[5] by pumping a group of four wells singly and in groups. The wells were 24 inches in diameter and from 33

[5] Unpublished records of tests made in Kansas by Vern C. Stambaugh under the direction of G. S. Knapp.

to 38 feet deep. The distance between the wells was 56, 73, and 92 feet. The depth to water was 11 feet. The water-bearing medium was fairly coarse sand and the casing which was of concrete was driven into the impervious layer below the sand. When these wells were pumped as a group, the average yield per well was 74 percent of the average yield of the wells when pumped separately. When these wells were pumped in pairs the average yield per well compared to the average yield of the wells when pumped separately showed the following reductions:

Distance between wells:	*Reduction in yield, percent*
56 feet	14.2
73 feet	8.7
92 feet	7.5
148 feet	5.3
221 feet	0.0

The results indicate that under the conditions of the test there was no particular advantage in spacing the wells farther than from 50 to 75 feet apart. It should, however, be kept in mind that if there were more than two wells in the battery, the interference would be somewhat greater.

TEST-HOLE DRILLING

Before starting to drill an irrigation well it is usually desirable to put down a test hole. The purpose of drilling test holes is to determine the location of the water table, the quality of the water, and the nature and location of the various formations encountered in order that it may be possible to decide whether conditions are favorable for obtaining a satisfactory well.

SAND-BUCKET METHOD

The most common method of putting down test holes is by means of a sand bucket or bailer. It is used most successfully in sandy formations, but in conjunction with a soil auger it may be used also in testing formations that contain layers of clay. It cannot be used in consolidated materials or formations that contain boulders. Accurate samples of the material encountered are obtained and the location of the different strata are definitely determined by this method. The procedure is the same as that used when drilling an irrigation well (p. 32) except that the hole is smaller and a smaller bailer is used. The test hole is cased with standard pipe which is pulled and used again after the test is completed. Any drilling rig with a hoist can be used for sinking a test hole with a bailer or sand bucket. In fact many of the test holes put down by this method are made by hand. A tripod with pulley, a sand bucket, and a rope are all the tools necessary. Two men can easily handle a 4-inch sand bucket such as is used for the work. This method is very satisfactory from the standpoint of cost and the accuracy of the results obtained, and is recommended for use where conditions are favorable.

STANDARD-TOOL METHOD

Where consolidated materials or layers of boulders are known to exist in the underlying formations, a standard portable rig and drop tools are used for drilling test holes. (See p. 32 for description.) In hard materials the holes are usually made either 4 or 6 inches in diameter. For holes of these diameters light tools having a 4- or 6-inch drill bit are used. The material in the hole is loosened by percussion of the drill bit, and is then removed with a bailer or sand pump. This procedure makes it possible to take accurate samples and to locate the different strata definitely. The test holes are cased with standard pipe or well casing. Lightweight casing such as riveted pipe cannot be used as it will neither stand the driving necessary to force the casing down nor the wear of the tools against it while drilling. Drilling test holes with standard tools is rather slow and is expensive, but it is the only satisfactory method in consolidated materials and in boulders.

HYDRAULIC-ROTARY METHOD

The hydraulic-rotary method is often used for drilling test holes. (See p. 57 for description.) It can be used only in drilling in unconsolidated materials, but under these conditions it is the fastest method known. Unfortunately the results obtained are not so satisfactory as those obtained by the methods previously described. Owing to the fact that clay is added to the water used in drilling, it is difficult to determine whether the formations encountered contain clay, and, furthermore, the fact that the drillings are carried to the surface continuously by the flow of clay and water mixture makes it impossible to determine accurately the depth from which the drillings caught at the surface are coming. Approximate results can be obtained very cheaply by the hydraulic process, but many drillers do not consider the information obtained sufficiently accurate for determining the possibilities of obtaining successful irrigation wells. Test holes drilled by this method are usually small, a 2-inch bit (fig. 37, A) on 1¼-inch pipe frequently being used. The hole drilled is slightly larger than the bit. A lightweight hydraulic-rotary rig is made for this type of work (fig. 6). It can be moved easily and requires much less power to operate it than the larger rigs. With a rig of this sort as much as 100 feet of hole can easily be put down in a day. No casing is required, but the hole should be kept full of water or there is danger that the material will cave and cause the loss of the hole.

JETTING METHOD

Another method of drilling test holes, known as the jetting method, is sometimes used in localities where layers of consolidated material are encountered that cannot be penetrated readily by the hydraulic-rotary process. A rig with a force pump and a spudding mechanism (fig. 7) is desirable, but for drilling shallow holes hand-operated equipment may be used. Drilling is done by means of jets of water

carried to the jetting bit (fig. 37, C) through the drill pipe. The bit is turned slowly by hand and after the material is loosened by the jet it is carried upward by the velocity of the water. Holes from 2 to 4 inches in diameter are usually put down. If the material in the hole tends to cave, the test hole is cased with standard pipe which is driven down as the jetting proceeds. If a layer of hard material is encountered, the drill is attached to the spudding mechanism on the rig. The drill rod and bit act as a percussion drill which, on account of its weight, is very effective in breaking up a hard formation. This method is very fast, but it has the same objection as the hydraulic rotary process as far as the accuracy of the results obtained is concerned.

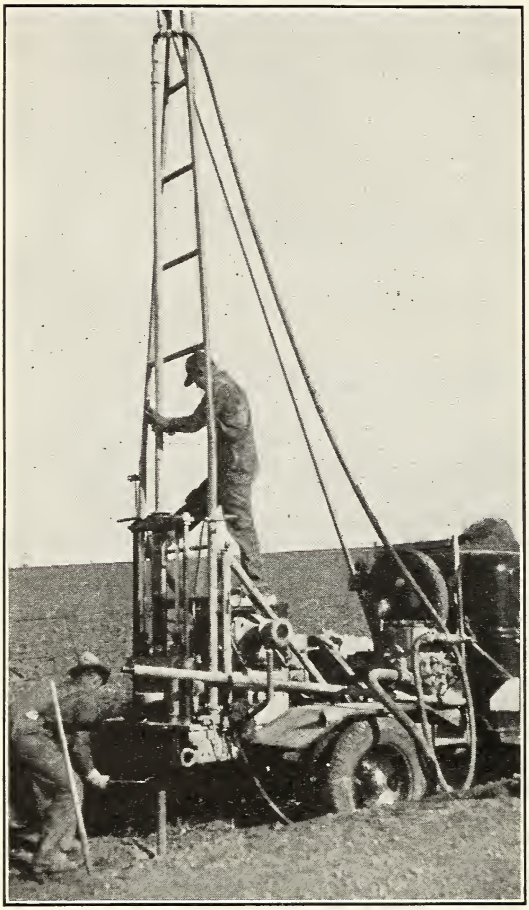

FIGURE 6.—A lightweight portable hydraulic-rotary rig for test-hole drilling.

HOLLOW-ROD OR SELF-CLEANING METHOD

The hollow-rod or self-cleaning method is sometimes used for drilling test holes for water. The equipment necessary consists of a hollow-drill bit with valve (fig. 37, B), a drill pipe, a swivel-hose connection, and some means for lifting and dropping the drill pipe. The spudding mechanism on a standard portable rig is frequently used (fig. 8), but it should be set to give a short stroke.

When the hollow-rod method is being used to drill a test hole, water is poured into the hole being drilled instead of being forced through the drill pipe as is the case when the jetting process is used. The reciprocating action of the drill forces the water and the drillings through the center of the drill and up the drill pipe. The valve in the drill bit prevents the water from running back once it has entered the drill pipe. Auxiliary ball valves in the drill pipe reduce the shock on the valve in the drill bit by supporting part of the water column. The drill pipe is turned slowly by hand in order to make the drill bit strike in a different place each time it drops.

Casing consisting of standard pipe is used in unconsolidated materials for the purpose of keeping the wall of the well from caving and the water in the hole from seeping away. Drive clamps are attached to the drill pipe, and the casing is then driven in the same manner as that used when drilling with standard percussion tools. Both the drilling and the driving operations put a severe strain on the drill pipe, and for this reason heavy pipe with special couplings is used. When the hollow-rod method is being used, the strokes of the drill must be carefully timed so that there will be a more or less continuous upward movement of the water through the drill pipe.

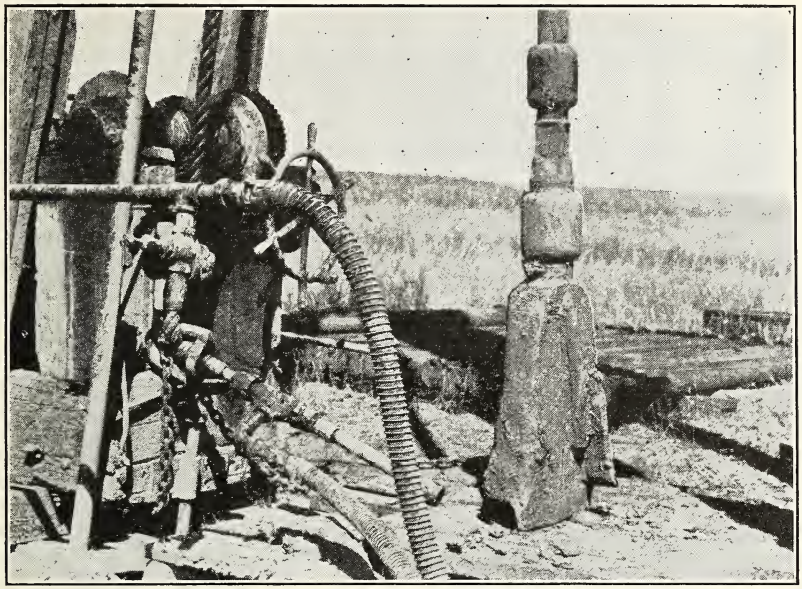

FIGURE 7.—Heavy-duty jetting rig used in drilling deep test wells.

This method is an improvement over the hydraulic-rotary process in that it can be used for drilling through hardpan and soft rock. Furthermore, the water-bearing strata can be definitely located and the samples obtained are more satisfactory because the material removed from the hole comes up through the drill pipe where it cannot be contaminated.

AUGER METHOD

A preliminary test of the possibilities of an area for supplying water from wells for irrigation is often desirable. If the water table is not too deep, the farmer can make the test himself by means of an auger and a long steel rod. A post-hole auger may be used for shallow holes. No casing is required. An old 1½- or 2-inch wood auger makes a satisfactory auger for this work when deeper holes have to be bored. The lips of the auger should be filed off if they have not already been worn away, and the shank welded to a piece of ¾-inch pipe threaded for pipe couplings. A handle for turning

the auger may be made from a tee and two 12-inch lengths of pipe threaded on one end. Enough 4-foot sections of pipe with couplings to make a hole of sufficient depth to reach the water-bearing formation are required. In boring the hole it is advisable not to fill the auger too full before attempting to pull it or it may become fast in the hole. As the joints in the pipe are all screw couplings, it is not possible to back the auger out without the danger of unscrewing the pipe in the hole. If the auger becomes fast an automobile jack set under a pipe wrench on the pipe will be found useful for loosening the auger. Sometimes the material encountered is so dry that it will not remain in the auger while it is being pulled. This situation can be corrected by pouring a little water into the hole from time to time.

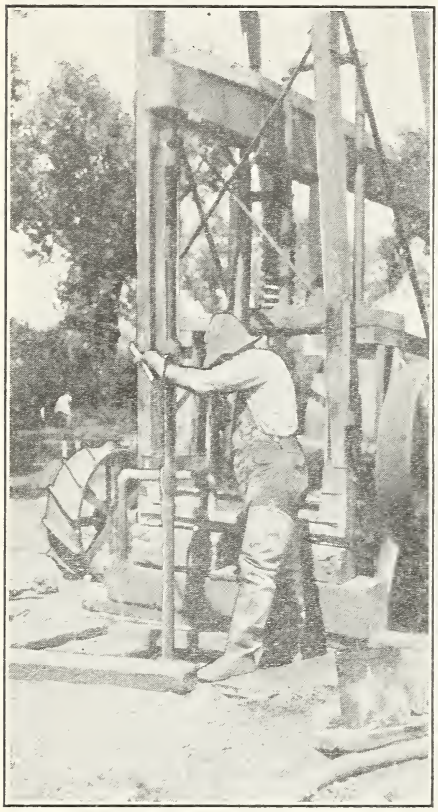

FIGURE 8.—Rig for drilling test holes by the hollow-rod of self-cleaning method.

When the water-bearing gravel is reached, the ordinary auger can no longer be used because it will not hold wet sand or gravel. Posthole augers of the bucket type can be operated in wet sand and gravel, but if the material is saturated, progress is slow because the sand and gravel wash into the hole from the sides. Further testing of the formation is done with the steel rod that is forced down into the sand and gravel until it reaches bedrock or strikes a boulder. The rod is forced down several times to make sure that bedrock has actually been reached. If possible, several additional holes should be bored in the neighborhood to determine the extent of the water-bearing formation and to check the data obtained from the first hole. These tests show merely the depth to water and the thickness of the water-bearing formations. They do not show the nature of the material. If, from these tests, the conditions look favorable for obtaining an irrigation well, a test hole should be put down by one of the methods previously described preferably with a sand bucket, in order to get samples of the water-bearing material.

LOG OF TEST HOLES

When drilling test holes a careful record should be kept of the thickness and location of the various formations encountered and of the depth to water. In addition representative samples, weighing

5 or 10 pounds should be taken of the water-bearing formations. The samples should be kept free from contamination by clay or other fine material from adjacent formations. Large samples should be taken so that there will be enough material to make a mechanical analysis of the sand and also a percolation test if necessary. The samples should be placed in cloth bags, tins, or glass jars for safe-keeping and each sample should be labeled so as to show the location of the well and the depth at which the sample was taken.

From the thickness of the layer of gravel and the samples, the experienced well driller can make a fairly good estimate as to the possibility of obtaining a satisfactory well, particularly if the well is in a locality with which he is familiar. The farmer should not attempt to pass on the samples himself. A sample of the gravel will also be of assistance to the casing manufacturer in determining the size of perforation that should be used in the well.

IRRIGATION WELLS AND THEIR CONSTRUCTION

The success or failure of well irrigation depends to a large extent upon the well. Pumps, motors, and engines have been perfected until they are highly dependable and efficient, but in order to have a successful pumping plant it is essential that the well be satisfactory also. It is impossible to get a good well when conditions are not favorable, but even when conditions are ideal it is necessary to choose the proper type of well and method of construction in order to get the most satisfactory results.

The types of wells most commonly used to obtain water from underground sources are driven wells, dug wells, bored wells, and drilled wells, according to the method of construction. There are other ways of classifying wells, but this arrangement is satisfactory and convenient. Of these different types the drilled wells are most important from the standpoint of irrigation as the number of drilled wells exceeds all the others taken together.

DRIVEN WELLS

A driven well consists of a pipe and sand point which are forced into the water-bearing material by driving with a wooden maul, drop hammer, or other suitable means. As the driving proceeds additional lengths of pipe are added until the desired depth is reached. A driving cap is used to protect the end of the pipe while it is being driven and the pipe is turned with a wrench to make driving easier. In order to prevent clay from clogging the screen of the sand point while being driven, it is frequently desirable to drill through formations of this sort with an auger.

Driven wells are usually from 1¼ to 3 inches in diameter, and standard-weight water pipe, either black or galvanized, with threaded couplings is used as casing. The sand point, also called a drive point, consists of a forged-steel or cast-iron point which is attached to a piece of perforated pipe. The perforated pipe is wrapped with a layer of fine-mesh brass screen and then covered with a sheet of brass perforated with small round holes. The perforated brass jacket protects the fine-mesh screen from injury while

the sand point is being driven. Several different screen sizes suitable for different types of water-bearing formations are available. Sand points may be obtained in a variety of lengths to suit the thickness of the water-bearing formation and the quantity of water required. A new type of drive point has recently been perfected consisting of spirally wound brass strips which are spaced so that they form a continuous slot of any desired width. These slots are narrower on the outside than on the inside and consequently do not clog easily with sand. These drive points also are made in various lengths. A typical installation of a driven well with a sand point of this type is shown in figure 9.

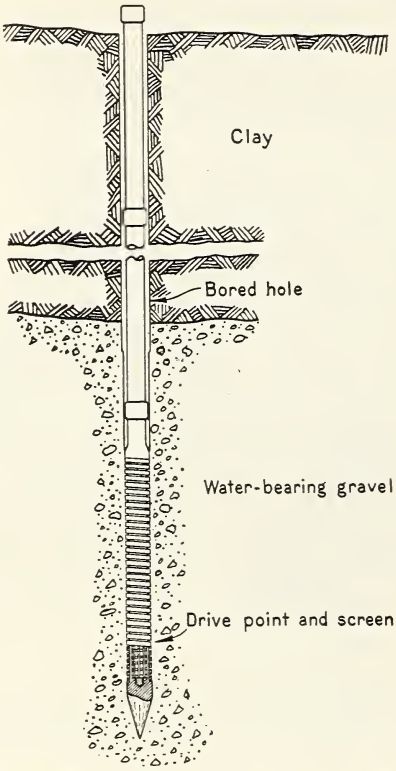

FIGURE 9.—Cross section of a driven well with modern drive point and screen.

Driven wells have long been used to supply water for domestic purposes, and batteries of these wells connected by a suction header to a single pump have recently been used to lower the water table over considerable areas. The yield from a single well is rather small, the maximum being between 20 and 50 gallons per minute, but the aggregate yield from a large number of these wells is sufficient to provide water for irrigation. Although there is no record of the use of driven wells for irrigation purposes, the use of a battery of them might be tried experimentally where conditions are favorable.

This type of installation is best suited to conditions where the water-bearing formation is free from large gravel and boulders that might injure the screen on the sand point, and where the water table is not more than 10 or 15 feet below the ground surface, because the pipe connecting the wells has to be near the water level in order to get sufficient draw-down in the wells to obtain the desired quantity of water without exceeding the suction limit. Although driven wells can be used in thick water-bearing formations other types are more effective, but in formations of limited thickness the driven wells probably give the best results. The yield from thin layers of water-bearing material is slight, and consequently small wells are adapted to this condition. The cost of these wells is small, and they have the further advantage that they can be put down by the farmer with little difficulty.

DUG WELLS

The first irrigation wells were large open pits excavated by hand and lined with wood, brick, stone, or special types of curbs. These pits were usually shallow and from 6 to 10 feet in diameter although sometimes larger. They seldom penetrated very deeply into the water-bearing formation and were frequently failures for this reason. Many of these wells had to be abandoned before they were completed because of the difficulties encountered in sinking them to the desired depth.

Dug wells are sometimes made rectangular or square, but the circular form is usually chosen, because it is stronger and it is also easier to construct. When the material will stand without support while being excavated, the hole is dug down to the water table without putting in a curb. The material is excavated with spades or shovels and after it is no longer possible to throw the excavated material out of the hole, a windlass or hoist with a bucket and rope is used to remove it.

The curb is started in the well as soon as the water table is reached or the walls of the pit begin to cave. Many different types of curbs have been used, but the commonest forms are the wood-stave and the ring types. The latter type consists of rings of brick, flat stones, concrete blocks, or cylindrical concrete sections which usually are laid on some form of shoe. The wood-stave curbs are made with either loose or fixed staves and are either square, rectangular, or circular in shape. In case the loose-stave type is used several rigid frames are built which are enough smaller than the pit that the staves may be placed in a vertical position on the outside of these frames and still leave sufficient room to feed in gravel between the staves and the wall of the pit. The staves should be beveled on the bottom from the inside and placed close enough together to keep the sand and gravel from coming through without offering any more obstruction to the passage of the water than necessary.

The staves are made 8 to 16 feet long depending on the depth to water and are usually 2 or 3 inches thick. As the excavating proceeds the staves are driven down one by one with a sledge or a wooden maul. The rigid frames hold the staves in place, and the beveled edge forces out the bottom of the stave as it is driven downward. The rigid frames are also driven down occasionally so that the lowest frame will always be near the lower end of the staves; otherwise the weight of the material back of the staves will force them inward. The upper ends of the staves should be chamfered and then wrapped with three turns of No. 10 soft steel wire to keep them from splitting while being driven.

When the excavation is about a foot below the water table, it will be necessary to install a pump to keep the water down so that the men will not be hampered in excavating the material from the bottom of the pit. A turbine pump is best suited for the work if electric power is available because it does not require priming and belts are not necessary. The pump sinks down as the excavating proceeds. Satisfactory results may also be obtained with a vertical centrifugal pump. As these pumps are usually belt driven, the pulley on the pump shaft will have to be reset frequently as the well gets deeper. A split pulley should be used for this purpose. A horizontal centrifu-

gal pump may be used for pumping the water out of the well, but in this case the pump must always be kept within 15 or 20 feet of the water surface so as not to exceed the suction lift. A gate valve is required on the discharge of a horizontal pump for the purpose of regulating the discharge so that it will not exceed the flow into the well. A foot valve in the suction pipe also is desirable as it will eliminate the necessity for priming each time the pump is shut off. Sinking pumps should be equipped with a substantial screen on the suction pipe to keep coarse gravel and rocks out of the pump. This screen should have a large area of openings and should preferably be short so that the pump will keep the water in the well at a low level. A sump should be dug for the pump suction, which should be kept a foot or two deeper than the well in order to keep the water level low. Sinking pumps are subjected to severe service on account of the amount of sand and gravel pumped, and for this reason new pumps should not be used for this work.

When the first set of staves has been driven down as far as possible, a second curb is built inside the first and in the same manner. This curb will reduce the size of the well considerably, and if a deep well is planned, which would require several curbs, the diameter of the well should be made large enough in the beginning to install the necessary number of curbs without reducing the well diameter too much.

Considerable difficulty is frequently encountered in sinking wells by this method because the pressure on the curb is augmented as the depth of the well increases, and when the water is removed from the well the pressure increases still more. This added pressure makes driving difficult. Furthermore, the weight of the material back of the curb and the velocity of the water under the ends of the staves causes the sand and gravel to wash into the well. If this washing continues, a hole will be formed which will ultimately cave in and may either crush the curb or distort it. To overcome this difficulty gravel is fed down on the outside of the curb to keep these cavities filled. If this precaution is not taken a large area around the well frequently begins to sink. This sinking is very likely to occur if a layer of fine sand is encountered which it is difficult to keep from running under the bottom of the staves. Sometimes as much as a foot or more of sand and fine gravel will come into the well at one time. This is known as heaving and usually occurs while the well is being pumped. It is frequently impossible to sink the curb under these conditions, and the well has to be abandoned. If it is possible to drive the staves down into the sand a considerable distance ahead of the excavation, it may be possible to keep the sand from coming in, otherwise a different method will have to be adopted for sinking the well if it must be dug deeper.

The fixed-stave type of curb, (fig. 10), which is frequently used in dug wells, consists of a cylindrical tube made of vertical timbers securely attached to a series of rigid frames in the shape of rings which are built up out of several layers of 2-inch lumber cut to form a circle. These rings are made with lapping joints and are securely spiked or bolted together. This type of curb is sunk in the same manner as the loose-stave type except that the curb is loaded with bricks or concrete blocks to force it down.

When a fixed-stave curb is used the water is removed from the well by the same methods as previously explained, and as the excavation proceeds gravel is fed around the outside of the curb to replace the material washed out. If the well is carried to bedrock, the bottom of the curb should be in contact with the bedrock, at every point, or there is danger of large quantities of sand and gravel coming into the well when it is pumped. If the curb is stopped in clay the excavation should be carried a foot or two into the clay so there will be no possibility of sand coming in under the bottom of the curb. If, however, the well is not carried down to a layer of impervious material the well should be backfilled with about 2 feet of coarse gravel to keep the sand from coming in under the curb. When the well is backfilled, a pit should be made for the suction pipe of the pump to

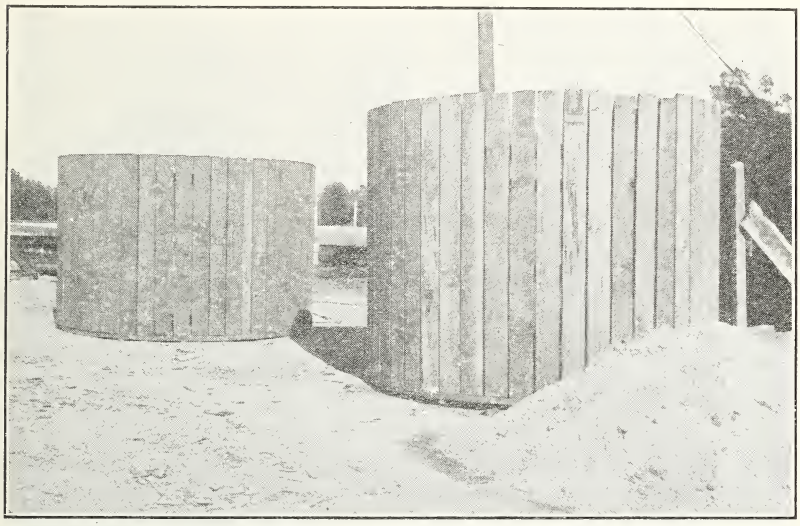

FIGURE 10.—Fixed wood-stave curb of type used in dug wells. Starter section shown on right.

keep the pump from sucking air when the well is being drawn to the limit. An oil drum with the head cut out and the sides punched full of holes makes a suitable lining for this pit.

Under favorable conditions this type of curb has been sunk 50 feet into the water-bearing formation, but under ordinary conditions 25 feet is about the limit when the hole has to be kept unwatered, and the digging is done by hand. Some of the difficulties encountered in sinking this type of curb may be eliminated by carrying on the excavation without unwatering the well. In this case the material is removed from the well with a sand bucket or an orange-peel bucket which is operated by a well-drilling rig or any equipment that has a hoist. Much better results are obtained by this method because the water in the well reduces the pressure on the curb and also tends to keep the sand from running into the well. If no boulders or layers of clay are encountered, this method works very satisfactorily.

Still another method of constructing dug wells consists of sinking a brick, concrete-block, monolithic-concrete, or large metal casing which also acts as the strainer. When bricks or concrete blocks are used for the curb, a strong shoe must be made upon which the curb is built. This shoe must be strong enough to support the curb, and to resist distortion. It is usually made of layers of planks similar to the rings used in the wooden curbs but much heavier. Sometimes a metal shoe is used. When the curb is made in this manner the inside corners of the bricks or blocks are broken off to provide passages for the water into the well. The bricks are laid flat. A single row is all that is required for small wells, but for large wells two rows laid end to end should be used and these should be tied together every four or five courses by a row of bricks laid side by side.

Monolithic-concrete curbs (fig. 11) are built in rings 3 or 4 feet high, and as the well increases in depth and the curbs sink down

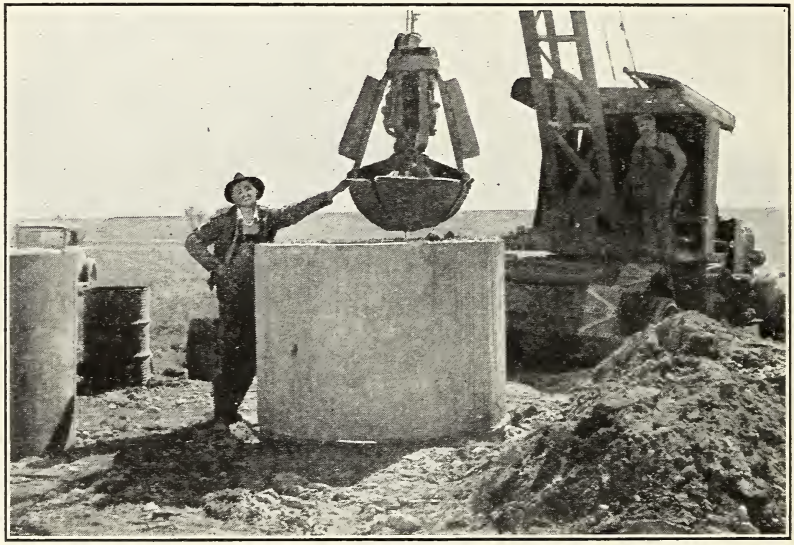

FIGURE 11.—Shallow well, 4 feet in diameter cased with concrete rings, being put down with an orange-peel bucket on a dragline.

additional rings are added. These rings are usually reinforced, and the individual rings are tied together by the vertical steel which is left protruding from the top of the ring when it is poured. Inside and outside forms should be used to obtain a smooth curb which will sink easily, and the portion of the curb in the water below the limit of draw-down should be perforated. The perforations are usually made by casting short pieces of 1-inch pipe, tin tubes, or pieces of garden hose in the curb. The holes in these tubes are plugged with clay before placing in the concrete and are cleaned out after the forms are removed. Several tubes should be placed in each square foot of area of the curb.

The large metal curbs are generally made of used material. The bottom of the curb is strengthened by a steel ring consisting of a heavy flat bar or an angle, and if the curb is not very rigid addi-

tional stiffening rings are added at intervals throughout the length of the curb. The curb is perforated below the limit of draw-down by punching it full of holes from the inside, by cutting slots with an acetylene torch, or by drilling holes from three-eighths to one-half of an inch in diameter. Best results will be obtained if the perforations are made before the curb is placed in the well. If the curb does not sink readily, it may be loaded on the inside with brick, but in that case an angle iron should be used instead of a flat bar for the stiffening ring at the bottom of the curb to support the tiers of brick.

These wells are generally excavated by hand with spades and shovels, but a sand bucket or an orange-peel bucket with a power hoist (fig. 11) may be used when no boulders, layers of clay, hardpan, or other consolidated materials are encountered. When a monolithic-concrete curb is being installed, coarse gravel should be used to keep the sand from coming through the perforations which are usually made large in this type of casing. The bottom of the well should be finished in the same manner as previously described. Under favorable conditions, brick or concrete-block curb wells can be dug from 15 to 20 feet into the water-bearing material, and greater depth can be attained with monolithic concrete or large metal casing.

Large-diameter wells, such as dug wells for providing water for irrigation, are best suited to conditions where the water table is near the surface and where the thickness of the water-bearing formation is not great. The large area of strainer permits the water to enter the well with a minimum loss of head and also reduces the velocity of water entering through the perforations. As a result, the tendency for the water to wash sand into the well is reduced. There is a general impression that large wells have much greater capacity than small ones for the same draw-down, but actually the advantage of the large wells in this respect is not nearly so great as is usually believed. Theoretically under ordinary conditions a well 8 feet in diameter has a capacity only 37 percent greater than a well 1 foot in diameter (*27, p. 264*). Under actual conditions the yield from the 8-foot well will probably be somewhat greater than this because the loss of head through the strainer will be less for the 8-foot well than for the 1-foot well. These large wells are much more expensive to construct than smaller wells, and it is doubtful whether the increase in capacity is sufficient to justify their construction under these circumstances. However, the pump and motor or engine may be installed in the well near the water table thereby making it possible to use a horizontal centrifugal pump where otherwise a deep-well turbine pump, which is more expensive, would have to be used. Although gasoline engines are frequently installed in large wells, the practice is a dangerous one owing to the possibility that gasoline fumes will accumulate in the well and explode when conditions are favorable. There is danger also from carbon monoxide poisoning.

The large open well is the type that the farmer most often attempts to put down. All he needs is a spade or shovel, two large buckets, and some form of hoist to bring up the excavated material. Actually, however, this is one of the most difficult types of wells to construct, and very often the farmer finds himself in trouble about the

time the casing has penetrated 2 or 3 feet of the water-bearing formation. The usual difficulties are that the casing gets out of plumb or collapses, the sand and gravel come into the well under the curb faster than they can be removed, the pump will not take care of the water, or the curb refuses to go down. As the result of these misfortunes the well has to be abandoned or an experienced well driller has to be hired to complete it. If the well is not in too bad a condition a good well driller can sink a smaller casing to the desired depth inside the first. If, however, the area around the well has sunk to a considerable depth and the casing is much out of plumb or badly collapsed it will probably be cheaper to start a new well. More satisfactory results will be obtained if the farmer digs the well down to the water table and then hires an experienced well driller to complete it.

The yield of dug wells depends largely on the depth they penetrate into the water-bearing formation, the better wells producing from 500 to 1,500 gallons per minute.

LARGE PITS

Large open pits excavated with a dragline or a steam shovel are sometimes used to supply water for irrigation. These pits are from 50 to 250 feet long and are of varying widths, the maximum being about 50 feet (fig. 12). They are excavated as deeply as possible

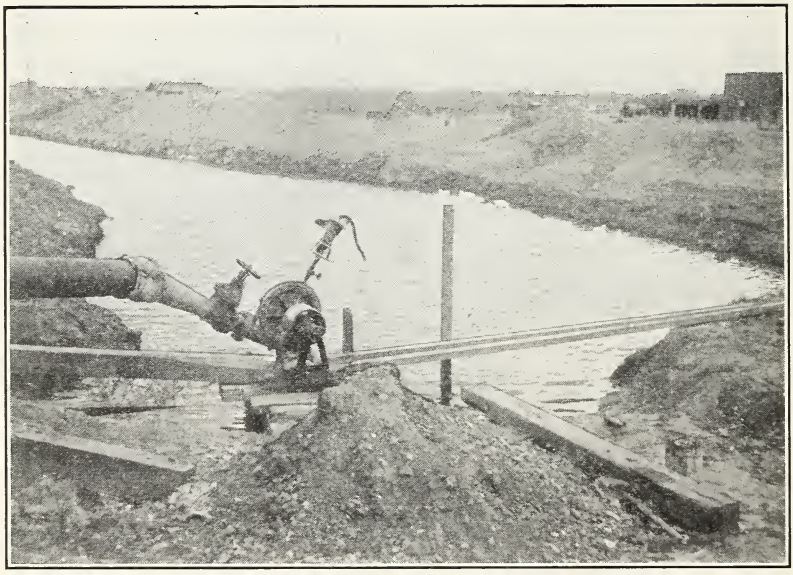

FIGURE 12.—Large open pit-type well excavated with dragline. Pit 50 feet wide, 100 feet long, and 18 feet deep.

into the water-bearing formation, but on account of the tendency of the sand and gravel to run into the pit owing to the constant agitation of the water by the excavating machinery, the maximum

depth of the pit below the water table seldom exceeds 8 or 10 feet. When pumping from the pit is started the entering water carries sand into the pit, and the removal of the water pressure on the inside of the pit causes the banks to slough thus partially filling it. The material excavated forms large unsightly spoil banks, and the area required for the pit and the spoil banks takes up valuable space. The sloughing of the banks makes it difficult to obtain a firm foundation for the pump. When the water-bearing material is fine, the large filtration area coupled with the considerable storage capacity of the pit should make it possible to get a satisfactory water supply, but the results obtained are usually poor because the small depth of water in the pit makes it impossible to get sufficient draw-down to force a large quantity of water through the fine sand into the pit. Better results would probably be obtained if a deep narrow trench were made so that a perforated pipe, laid horizontally and connected with a pump sump, could be placed in the bottom of the trench at a considerable distance below the water table and then covered with coarse gravel. Although such a well would have very little storage capacity it would probably yield more water than the large pit because it would be possible to draw the water down to a greater depth. Pits yielding 1,000 gallons per minute are rare.

BORED WELLS

Augers are sometimes used to put down irrigation wells to the point where unconsolidated water-bearing material is encountered. These wells are called bored wells, and the augers used to construct them are similar to post-hole augers but are much larger and are more substantially made (fig. 13). They consist of a cylindrical steel bucket with a cutting edge along a slot in the bottom. The bucket is filled by turning with a power-driven rotating mechanism. The turning motion is imparted to the auger through a square stem which slides down through a hole of similar size in the rotating mechanism as the well gets deeper. A hoist is required to lower and raise the auger. After the auger has been brought to the surface the material excavated is removed through a door in the side of the bucket. The augers are made in different sizes, but a reamer is used when it is desired to make a hole larger than the size of the auger. The reamer is attached to the top of the bucket in such a manner that the material excavated when enlarging the hole is carried into the bucket at the top. Holes up to 32 inches in diameter and sometimes larger are made by this method.

Augers work most satisfactorily where the walls of the holes do not cave. Casing may be used, but it is difficult to force the casing down because the rotating mechanism is in the way. As soon as unconsolidated water-bearing material is encountered other methods have to be adopted for completing the well. Augers may be used, however, to cut through layers of clay that sometimes occur in the water-bearing formation.

When conditions are favorable, rapid progress can be made with this type of equipment. From 5 to 10 feet can be excavated per hour in shallow holes, but the rate decreases when the holes get deeper.

Where equipment for boring wells is available and the material to be excavated does not contain boulders or large roots, this method is very useful. The yield of bored wells ranges from 500 to 1,500 gallons a minute, depending on the water-bearing medium.

DRILLED WELLS

Wells put down by means of percussion drills, rotary drills, water jets, or modifications of these tools are known as drilled wells. The methods used in drilling wells are classified as the standard method, the California or stovepipe method, the sand-pump or orange-peel-bucket method, the hydraulic-rotary method, the jetting method, and the hollow-rod or self-cleaning method (*1*). At present most irrigation wells are being put down by one of these methods.

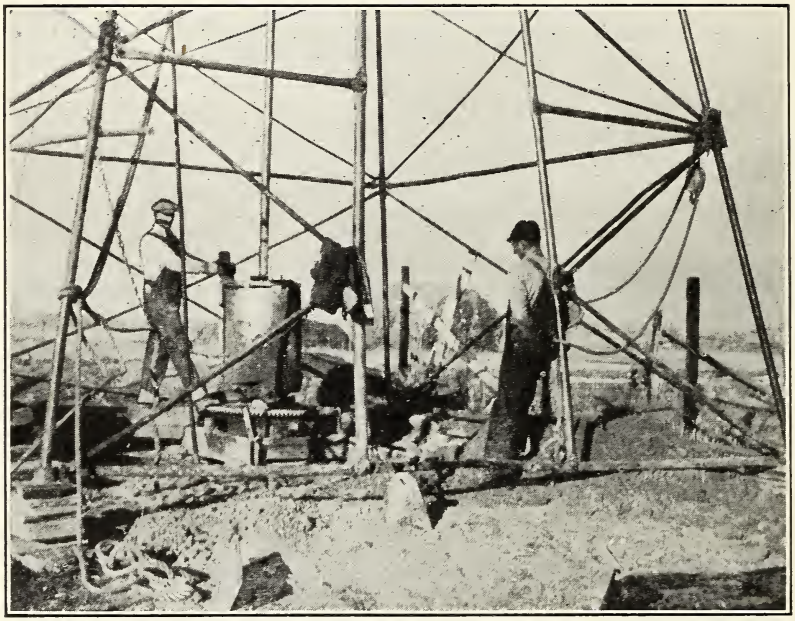

FIGURE 13.—Drilling 30-inch well in clay with an earth auger.

STANDARD METHOD

Wells put down by the standard method are drilled with a standard rig (fig. 14) and percussion tools in conjunction with a bailer which is used to remove the drillings from the hole. This method is adapted to drilling deep holes in consolidated material, such as rock, and is sometimes used in shallow holes when drilling through boulder formations. Holes from 3 to 24 inches and more in diameter can be drilled but most irrigation wells are from 12 to 24 inches in diameter. The principle upon which the drilling is accomplished when using standard tools is the breaking of the rock by the impact of a bit with a relatively sharp chisel edge which is lifted and

dropped at regular intervals, and which is at the same time slowly turned by hand so that the edge of the bit strikes on a different line at each successive blow. If the tools are sharpened properly and are turned carefully, the bit will cut a round straight hole.

TOOLS AND EQUIPMENT

A complete string of standard tools (fig. 15) is made up of a drill bit, a stem, a set of jars, a sinker bar, and a rope socket. It may weigh as much as 5,000 pounds. The tools are subjected to very hard service, and in order to withstand this service special steels must be used in their manufacture. The tools are joined together by screw joints of the box-and-pin type. These joints, having a pronounced taper, can be made up so tightly that even the constant jarring of drilling will not loosen them. Special wrenches which fit the squared sections of the tools are used to tighten the joints.

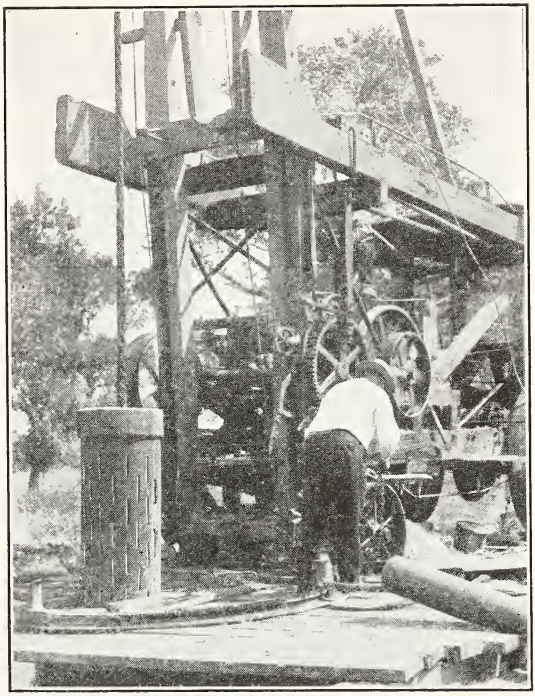

FIGURE 14.—Large portable standard rig drilling 20-inch irrigation well with percussion tools in boulders. Slot-type perforated casing is being used.

The bit is the most important part of the string of tools. It does the actual drilling and consists of the cutting edge, the body, the wrench square, the shank, and the pin. Different shapes of bits are made for different purposes. Some of the different forms are shown

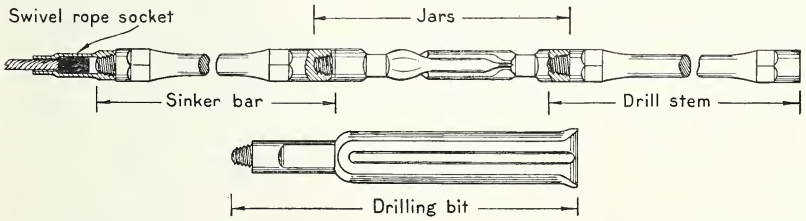

FIGURE 15.—Typical string of tools used on a standard rig. A regular pattern drilling bit is shown.

in figure 16. The regular drill bit (fig. 15) is the type generally used in drilling rock. The Mother Hubbard bit (fig. 16, *A*) is similar to the regular bit except that it has square instead of round shoulders. It is used because the sharp shoulders of the bit ream out the hole easily where the mud from drilling materials such as shale builds up on the sides of the hole. The California pattern bit (fig. 16, *B*) has long sloping shoulders and is used in drilling large holes in hard formations and where the drilling is carried on ahead of the casing. The sloping shoulders do not catch on the bottom of the casing when the tools are being withdrawn. Star-pattern bits (fig. 16, *C*) have two cutting edges at right angles to each other. They are used for drilling in fissured and tilted rock because the additional cutting edges tend to keep the hole round and straight. Spudding bits (fig. 16, *D*) are short and thin and are used in starting holes in soft formations. Various special types of drills, not shown, are made for the purpose of performing particular functions, such as reaming, undercutting, or straightening the hole.

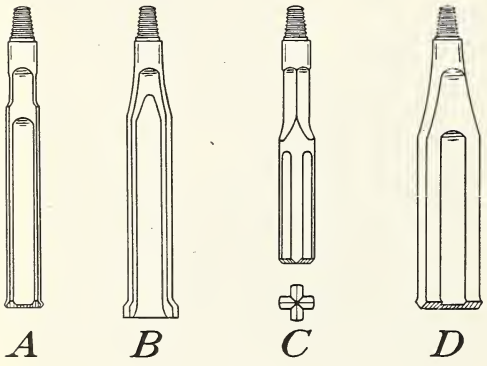

FIGURE 16.—Different patterns of bits used on a standard drill rig: *A*, Mother Hubbard; *B*, California pattern; C, star pattern; *D*, spudding.

The drill stem (fig. 15) consists of a round steel bar which is connected to the drill bit by a box-and-pin joint as previously explained. The purpose of the stem is to add weight and length to the drill so that it will cut rapidly and will make a straight hole. Stems vary from 6 to 30 feet in length and from 2½ to 6 inches in diameter. The weight varies from 100 to 3,000 pounds.

The sinker bar is similar to the drill stem in shape, only shorter. It is occasionally used to give additional weight and length to the string of tools.

The jars (fig. 15) consist of a pair of narrow steel links with a box joint on the lower end for attaching them to the drill stem and a pin joint on the upper end for attaching the rope socket or the sinker bar if one is used. The purpose of the jars is to provide a means for giving an upward blow to the tools in case there is a tendency for them to stick in the hole. They have very little effect on the downward blow struck by the bit when drilling. Jars are also used on fishing tools, and in this case the drill stem is frequently attached above the jars so as to give a harder blow to the tools. The stroke of jars varies, depending on the nature of the work being done, the heavier the blow required, the longer the stroke. For light work, such as drilling, the stroke is from 6 to 8 inches, but, where a blow of maximum force is necessary, jars with as much as a 36-inch stroke are provided.

Rope sockets (fig. 15) are for the purpose of attaching the rope or cable to the string of tools. They are made both with and without a swivel joint although when using a wire cable, the swivel-type socket is generally used. Wire cables are held in the socket by pouring melted zinc or babbitt around the unraveled end of the cable after it has been threaded through the neck of the socket. Manila ropes are held by pointed rivets driven through the neck of the socket after the end of the rope has been tightly wrapped with twine and forced into the socket.

The drilling tools are suspended by either a wire cable or a manila rope. Manila ropes are more elastic and cause less shock to the rig when drilling, but they wear out very rapidly, and for this reason wire cables are more generally used. Manila ropes are still used by some drillers in starting holes because the lack of elasticity in wire cables is particularly noticeable when drilling with a short cable. Wire cables used in drilling vary in size from ½ to 1 inch in diameter and manila ropes from ¾ to 2¼ inches. The largest sizes are used only when drilling deep holes with heavy tools. On large rigs a temper screw is used to feed out the cable so that the bit will strike the rock with a blow of maximum cutting power, but on small rigs the adjustment of the length of the cable is made by winding or unwinding the cable from the reel on the drilling rig.

When a standard rig is used the drillings are removed from the well by means of a bailer or vacuum sand bucket (fig. 17). A bailer consists of a section of pipe generally from 8 to 20 feet long with a

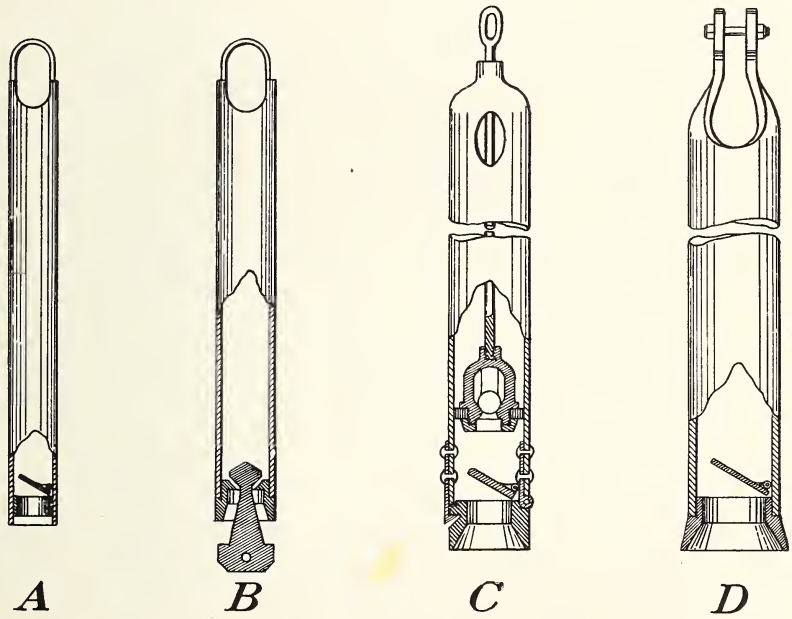

FIGURE 17.—Sand buckets or bailers with different types of valves and a California mud scow: *A*, flapper valve; *B*, dart valve; *C*, bayonet valve; *D*, mud scow.

valve in the bottom and a bail at the top for attaching the drilling cable or the sand line, whichever is used. The diameter of the bailer is determined by the size of the hole being drilled, plenty of clearance being allowed so that the bailer will fall freely. Bailers are equipped with flat, dart, or bayonet valves. The purpose of these valves is to allow the drillings to enter the bailer and to keep them from running out after they have been caught. The opening in the valve should be as large as possible in order to permit rocks and balls of clay to enter the bailer easily. The flat-valve bailer has a flapper valve which cannot be opened after the bailer is filled (fig. 17, *A*). This type has to be emptied by turning it up on end. Bailers with dart valves are emptied by striking the dart attached to the valve on something solid which forces the valve open (fig. 17, *B*). Bailers with the bayonet-type valve (fig. 17, *C*) have the valve mechanism in a hinged portion of the pipe, which is released by opening a latch.

The vacuum sand pump is similar to a bailer except that it is equipped with a piston for the purpose of drawing the drillings into the bailer (fig. 17, *C*). The piston is attached to the hoisting cable, and when the sand pump reaches the bottom of the hole the piston sinks to the bottom of the bailer. The weight of the sand pump holds it on the bottom of the hole while the piston is being raised, hence this type is more effective than the ordinary bailer in clearing out the hole.

The standard portable rig consists essentially of a mast, a two- or three-line hoist, a walking beam, and an engine, all of which are mounted on a frame having steel or rubber-tired wheels so that the rig can be transported easily from place to place. The mast is made long enough to allow the longest string of tools or section of pipe to be hoisted out of the hole, the minimum height being about 30 feet. The mast is hinged so that it may be folded up and carried on top of the rig when the equipment is moved. The sheave for the drilling line is usually mounted on springs or rubber to take up some of the shock when drilling is in progress. The hoists consist of power-operated reels large enough to hold sufficient cable for drilling the deepest holes of which the rig is capable. The reels are driven by friction pulleys or by positive drives such as gears or chains. When a positive drive is used a clutch has to be provided for each reel to throw the mechanism in and out of gear. The sand-line reel is smaller than the drilling-line reel and usually operates at a higher speed. The drilling-line reel has to have sufficient power to hoist the tools and the cable out of the hole, and to operate fishing tools and other equipment. Long strings of casing also have to be raised or lowered by the drilling-line hoist. If an additional hoist is required to operate special equipment a separate reel is provided. All the reels are equipped with powerful brakes capable of stopping or holding them at any time. In addition the drilling reel is equipped with a hand-operated slow-motion drive for the purpose of raising or lowering the cable a small amount while drilling. This device takes the place of the temper screw.

The walking beam is a heavy hinged arm with a sheave at one end through which the drilling line passes. A pitman, which is oper-

ated by a crank driven by the engine, is attached to the walking beam near the sheave end. As the crank rotates, the walking beam moves up and down. The sheave at the end of the walking beam also moves up and down and as a result raises and lowers the drilling line. Since the end of the line on the reel is held fixed by the brake the tools which are attached to the other end of the line rise and fall. This is the motion that causes the drill to operate. The length of the stroke depends on the radius of the crank arm, which may be varied by changing the setting of the crank pin. The experienced driller adjusts the length of the stroke and the number of strokes to the minute to suit the work. When the equipment is adjusted properly the drilling proceeds at a maximum rate with minimum vibration and jerking.

Steam engines were formerly used to operate portable well-drilling rigs, but gasoline engines are now used almost exclusively. Single-cylinder engines are used on small rigs, but on the larger rigs where more power is needed 4- and 6-cylinder engines are used because they are lighter and more flexible. For small rigs a 7- or 8-horsepower engine is all that is necessary to operate the rig, but for large rigs from 20- to 40-horsepower engines are required. A belt drive is usually employed to transmit the power from the engine to the walking beam and the hoists.

AUXILIARY EQUIPMENT

In addition to the equipment already described, a large number of accessories, such as drive clamps (fig. 18), drive heads, casing rings and slips, jacks, casing elevators, tool wrenches, tool-wrench tighteners, pipe wrenches, and some of the common types of fishing tools are also required.

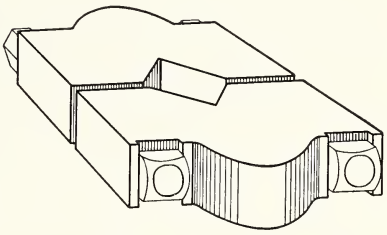

FIGURE 18.—Drive clamp used to drive casing.

DRILLING OPERATIONS

When the standard method for putting down irrigation wells is used, the drilling, as previously explained, is done by raising the tools by means of the walking beam and then allowing them to drop so that the bit strikes the material in the bottom of the hole. The tools make from 25 to 50 strokes per minute and by turning the drilling cable back and forth, the bit rotates also and in so doing makes a round hole. As the hole grows deeper more cable is let out so that the tools will always be striking the bottom of the hole with blows of maximum cutting power. If no water is encountered in the well, water is added from time to time. The water mixes with the drillings and forms a paste which does not reduce the force of the blows of the bit nearly so much as the dry material. Too much water in the hole, however, interferes with the progress of the drilling because of the buoyant effect of the water on the string of tools and the friction of the cable in the water.

When the bit has cut 4 or 5 feet into the rock or other material the tools are withdrawn and the drillings are cleaned out of the hole with a bailer or sand pump. Several trips are usually required to do this. When the hole is clean, the tools are lowered to the bottom of the hole and drilling is resumed. If the drilling is being done in a dry hole water has to be added to replace that taken out in removing the drillings.

Each time the string of tools is withdrawn the bit is inspected to see whether it is too dull to drill rapidly or worn too small to cut a full-size hole, and if so the bit is replaced with one newly sharpened. The joints in the string of tools are inspected also to see whether any of them have worked loose. Each joint is marked with a chisel cut across the joint, and it is only necessary to note whether the parts of the cut are in alinement to see whether the joint has unscrewed. If any joint has loosened, it is again tightened by means of the tool wrenches.

In hard rock unless much water is encountered the hole is not cased, but in soft material casing is used to keep the hole from caving. As the drilling progresses, the casing is driven down by means of the tools and the drive clamps. It is customary to keep the end of the pipe near the bottom of the hole so as to avoid the danger of the hole caving in, and in some materials the casing is forced ahead of the tools. When layers of quicksand are encountered, difficulty in driving casing usually occurs, and unless the casing is forced through the layer, the sand will keep running into the well when bailing or sand pumping is attempted. Under these circumstances, clay is dumped into the well and then mixed with the quicksand by churning with the tools. This forces the clay out of the casing into the quicksand surrounding the casing and forms a barrier through which the sand cannot come. The casing is then driven as far as possible, and after bailing out the hole, more clay is added. This procedure is repeated until the casing is driven through the layer of quicksand. Progress by this method is slow, and if it is anticipated that a large amount of quicksand will be encountered, some other method, such as the rotary method which will be described later, should be adopted for drilling the well or that portion where the layers of quicksand are located.

CASING

Wells drilled by the standard method are cased either with standard pipe or well casing. Light casing cannot be used satisfactorily because it does not withstand driving successfully, nor is it strong enough to resist the wear of the tools against the casing while drilling is in progress. For ordinary work where heavy driving is not required, well casing is used. It is lighter in weight than standard pipe and also cheaper. It is made with either common sleeve couplings or inserted joints. Inserted-joint casing has one end of the pipe threaded on the outside and the other end, which has been expanded slightly, threaded on the inside. This type of joint will not stand much driving. When it is anticipated that hard driving will be necessary, standard pipe is used. This pipe comes in three weights; standard, extra strong, and double extra strong. These pipes are threaded on both ends, and the joints are made by screwing the ends of the pipes into sleeve couplings. For heavy driving the couplings are made so that the pipe can be screwed into the coupling

until the ends of the pipe butt together. In this way the threads on the pipes are protected to some extent because the ends of the pipe bear part of the load.

The sizes of standard pipe refer to the inside diameter. Extra strong and double extra strong pipe, however, have the same outside diameter as standard pipe, the additional thickness being obtained by making the inside diameter smaller and consequently the same fittings may be used on heavyweight pipes as on standard pipe. The size of well casing is based on the outside diameter. The threads of casings are finer than those on standard pipe, because the casing is thinner. Fittings for standard pipe will not fit well casing. The farmer should keep these differences in mind, and when ordering pipe should specify the kind desired, and when ordering fittings, should indicate whether they are for standard pipe or for well casing.

A drive shoe should always be used when driving either standard pipe or well casing. The shoe is made of forged steel and is either screwed or welded to the bottom of the first section of pipe. The shoe has a beveled edge for cutting and is made strong enough to withstand heavy driving without failure or distortion.

In shallow irrigation wells the hole is sometimes cased with standard pipe or well casing while the well is being drilled, and when the well is completed a string of lightweight riveted pipe which has already been perforated is installed in the hole inside the casing after which the heavy outside casing is pulled out for use elsewhere. If the well is in fine material, screened gravel may be placed in the space between the two strings of casing while the outside casing is being pulled. The gravel will act as a strainer to keep the fine sand from coming into the well.

Casing used in irrigation wells has to be perforated where it passes through water-bearing formations in order to let the water into the well. Some casing is perforated before it is put into the well, but in most instances when using the standard method, the casing is perforated in place after the well is completed. The perforations consist of slots, and the size and number of the slots required depend on the nature of the formation and on the water supply. The perforations are usually placed in rings with not more than one slot for every inch of pipe diameter. The slots in preperforated pipe are either punched or are cut with an oxyacetylene torch (figs. 14 and 38). Casing in place in the well is perforated by means of a Mills knife (p. 46) or a similar type of perforator. Screens or strainers of the type used in wells for domestic water supplies which consist of slotted brass tubes or spiral bands on a cylindrical form are seldom employed in irrigation wells. Strainers with sufficient capacity to supply water for this purpose would be too expensive to use in irrigation wells.

ADAPTABILITY OF STANDARD METHOD

The standard percussion-tool method of drilling wells may be used under a variety of conditions, but it is most useful in drilling in hard rock, fissured formations, and boulders. Although the standard portable well rig is designed primarily for drilling with percussion tools, with slight changes it may be used for drilling wells by other methods. In fact, when drilling in formations of a variable na-

ture it is customary to change from one method to another. For these conditions the standard portable rig is particularly well suited. The standard method of well drilling is not, however, adapted for use by the farmer in drilling his own well. The use of this method requires an experienced well driller on the work, or the outcome is almost certain to be unsuccessful. For this reason the farmer whose well will penetrate formations requiring the use of this method should take special pains to secure the services of an experienced and successful driller.

THE CALIFORNIA OR STOVEPIPE METHOD (MUD-SCOW METHOD)

The California or stovepipe method of drilling wells is an adaptation of the standard method. Percussion tools are used, but instead of standard tools and a bailer, a device known as a mud scow (fig. 17, D) is employed which combines the functions of the drill and the bailer. Hydraulic jacks are used to force down the casing. All the equipment is operated by a California rig (fig. 19) which is similar

FIGURE 19.—California rig drilling well with standard tools and mud scow. Standard tools are on drilling line and mud scow is on ground near well.

to a standard rig but usually much heavier. This method was developed in California for drilling large relatively deep wells in unconsolidated material such as clay, sand, gravel, and boulders, to supply water for irrigation. It is not suitable for drilling in hard consolidated materials, but the equipment used in the California method may be utilized to operate standard percussion tools. If a layer of very hard material is encountered, the mud scow is replaced by a string of tools and drilling is continued by the standard method until the hole is driven through the hard layer.

TOOLS AND EQUIPMENT

The string of tools used on a California rig consists of the mud scow, a pin-and-tongue substitute, fishing jars, and a rope socket. The mud scow is made from a section of heavy pipe and is equipped with a flat valve having a large opening so that it will not be clogged easily by clay balls or small rocks. A heavy shoe of special steel is welded to one end of the pipe, and a pair of ears is formed on the other end by cutting away a part of the pipe or by riveting or welding a pair of straps on the inside of the pipe. The ears are drilled for a large-size pin which fits the hole in the pin-and-tongue substitute and forms a knuckle joint between the mud scow and the jars. The joint makes it possible to tip the mud scow up on end to dump it. For drilling in clay a special type of mud scow is used which has a cutting edge welded across the bottom of the shoe. This cuts the clay into small chunks so that it will not get caught in the valve at the bottom of the mud scow. A special type of mud scow is used also for under reaming. It has a deflector plate just above the shoe and an outlet for the water through the side of the pipe opposite the deflector. When the mud scow drops through the water, the deflector plate forces the shoe against the side of the hole, and as a result increases the diameter of the well.

Fishing jars having a stroke of from 18 to 36 inches are used when drilling with the mud scow. The jars are connected to the mud scow by means of a substitute that has a tongue with a hole in it at one end and a pin at the other end. The jars are attached to the drilling cable by a rope socket which is similar to those used on standard tools except that for light work a wing socket is sometimes used. The end of this socket is split so that the wings may be sprung apart for inserting the rope. After the rope is inserted the wings are riveted together by pointed rivets which are driven through the rope. For convenience in disconnecting the rope from the tools, jaw sockets are sometimes used as the removal of the pin is all that is necessary to disconnect the drilling line.

The California well rig consists of a mast, a hoist capable of operating two or more lines, a pressure pump, an engine, and a walking beam. The principal difference between a standard rig and a California rig is that the walking beam on the California rig is at the top of the mast instead of in the body of the rig. The walking beam is about 10 feet long and is made either of wood or steel. It is pivoted near the center on a spring-mounted support that takes some of the jar off the rig and the cable while drilling. The front end of the walking beam carries the crown pulley and the sand-line

pulley. The rear end of the walking beam is attached by tail rods to the crank that gives the walking beam its reciprocating motion. Tail rods are usually made of heavy pipe, but wood is sometimes used. Some rigs are equipped with a cable between the crank and the rear end of the walking beam instead of a steel or wood rod.

The mast on the California rig is about 36 feet high and is made heavier than the mast on a standard portable rig in order to take care of the additional load imposed by the operation of the walking beam. It is usually made of timber in the form of an A frame and is braced by two diagonal struts attached to the top of the mast and the frame of the rig. Lateral stability is obtained by the use of guy wires. The frame of the rig is made very strong to carry the weight of the hoisting machinery, the engine, and the pressure pumps, as well as the load from the walking beam. The rig is equipped with four wheels that are usually removed and replaced by heavy sills when the rig is being set in position preparatory to drilling. Steam power was originally used on California rigs, but at present most rigs are equipped with gasoline engines. The hoisting equipment is similar to that used on a standard rig.

The pumps for supplying pressure to the hydraulic jacks that are used to force the casing down, are located on the side of the drill rig. These pumps are of the double-acting type and are very substantially made as they develop pressures up to 4,000 pounds per square inch. The hydraulic jacks have barrels from 3½ to 6 feet in length and from 4 to 8 inches in diameter depending upon the length of the sections of casing and the force required. These jacks have to be built strong enough to withstand the maximum pressure developed by the pumps. They are double acting so that they may be used either to force the casing down or to pull it out in case the well has to be abandoned. The jacks are set in a vertical position close to the casing in the manner shown in figure 20. The setting of the jacks is very important because the pull on the foundation may amount to several hundred tons. Either two or four jacks are used. Levers loaded with sandbags are sometimes employed to force the casing down when drilling shallow wells by this method (fig. 21).

A heavy steel cap with two or four lugs on the sides for attaching the jacks or levers is placed on top of the casing to keep from crushing it when the force is applied by the jacks or levers. This cap has to be removed each time a new section of casing is added as the drilling progresses. This is conveniently done by passing a wire-rope sling through the link of the jars and then attaching the loops to the lugs on the cap. When the mud scow or the standard tools are withdrawn from the well, the heavy cap is lifted also. Sometimes the mud scow is so large that it will not go through the hole in the casing cap. In that case it is necessary to lift the cap in the manner just described every time the mud scow is withdrawn from the well. The heavy cap assists in dumping the mud scow by causing the top of the bucket to drop lower than the bottom when it is lowered over a frame which acts as a fulcrum for the bucket.

DRILLING OPERATIONS

When drilling a well by the California method the mud scow is raised and dropped in the same maner as a standard string of tools. The drilling is done by the impact of the cutting edge of the mud scow on the material in the hole. The tension of the drilling line and the stroke of the tools are adjusted so that the drilling proceeds at the maximum rate. The usual speed is from 30 to 40 strokes per minute. As the hole deepens the mud scow is lowered by letting out more cable. The drillings are drawn into the mud scow through the valve in the bottom and as soon as the mud scow is full it is hoisted to the surface and dumped. If the hole is dry it is necessary to add water from time to time. When the material is dry and porous an open pit is often dug by hand to the water table. Some of these pits are more than 100 feet deep.

As drilling proceeds the casing is forced down into the hole by means of the hydraulic jacks. The shoe of the casing is kept within less than the length of the mud scow of the bottom of the hole except where the material will stand without caving. As the casing is forced down more sections of casing are added.

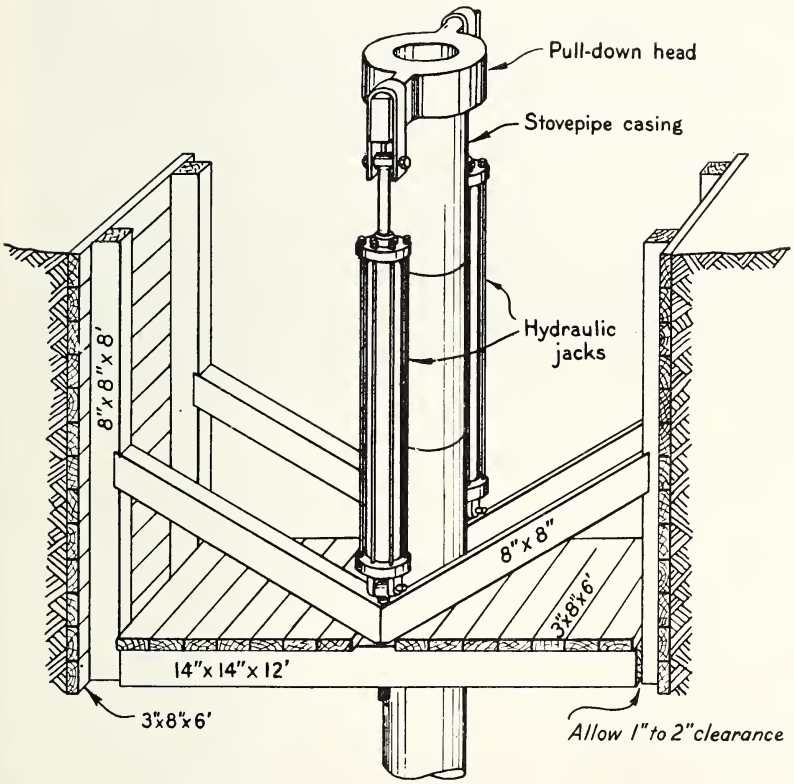

FIGURE 20.—Hydraulic-jack installation for forcing down California stovepipe casing.

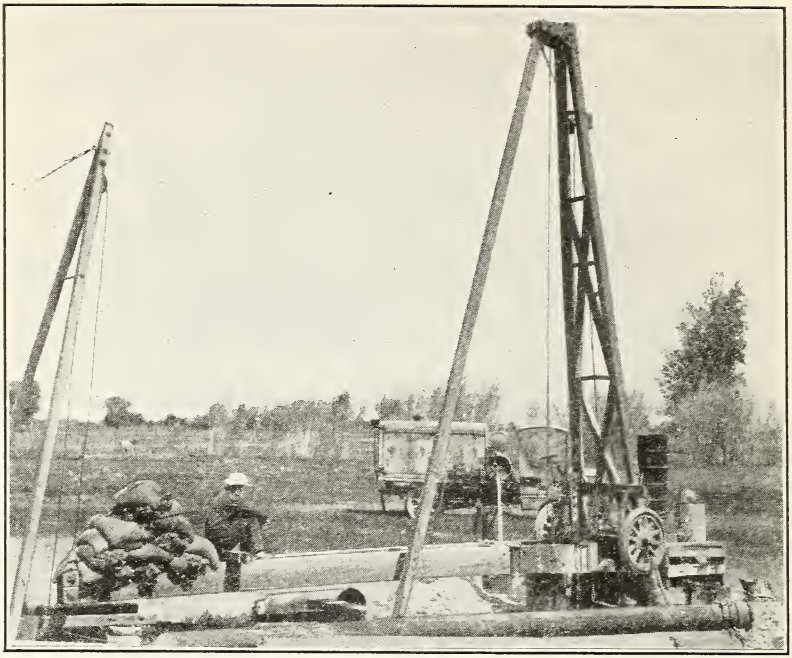

FIGURE 21.—Stovepipe casing being forced down into shallow well by means of lever loaded with sandbags.

STOVEPIPE OR DOUBLE WELL CASING

The type of casing used in the California or stovepipe method of drilling wells is unique. It is made up of inside and outside sections (fig. 22) which telescope into each other and form a casing of two thicknesses of metal with a joint in the middle of each section. The sections are made usually with vertical single-riveted lap or welded joints. The sections are made so that they fit together closely, and considerable force has to be applied to drive them together. The ends of the sections are faced in a lathe so that they will butt together evenly and squarely and not slip by each other when they are forced together. After each section is added it is dented with a special pick for the purpose of keeping the sections from slipping apart in the well. Sometimes the sections are riveted or welded together to keep them from coming apart. The latter method should be used in case it is anticipated that the casing may have to be pulled.

Stovepipe casing is made of what is known as hard red steel. The thickness used varies with the nature of the formations and with the depth and diameter of the well, 8- or 10-gage steel being used in deep wells when hard driving is required, and 16-gage, in shallow wells of small diameter. Stovepipe casing is made in all diameters from 4 to 36 inches, but the 16-inch size is the one most commonly used. It is made in 24-, 36-, and 48-inch lengths depending on the size of the pipe and the gage of the material.

The first section of casing, when starting a well, is assembled before being placed in the well. This section, called the starter,

usually consists of from 9 to 20 feet of two-, three-, or four-ply casing which is riveted or welded together and attached to a heavy drive shoe. The length and thickness of the starter depends on the depth of the well and the nature of the material into which the hole is to be driven. The drive shoes are made of steel and are recessed on the inside so that when they are attached to the starter sections the joints will be flush on the inside and the bottom of the casing will butt against the shoulder in the shoe. Drive shoes, or well rings as they are sometimes called, are made in various sizes, and where it is anticipated that difficulty will be encountered in forcing or driving the casing down, forged-steel shoes or heavy shoes, some of them as much as 1½ inches in thickness, are used. In some cases no starter is employed, the sections of casing being placed directly

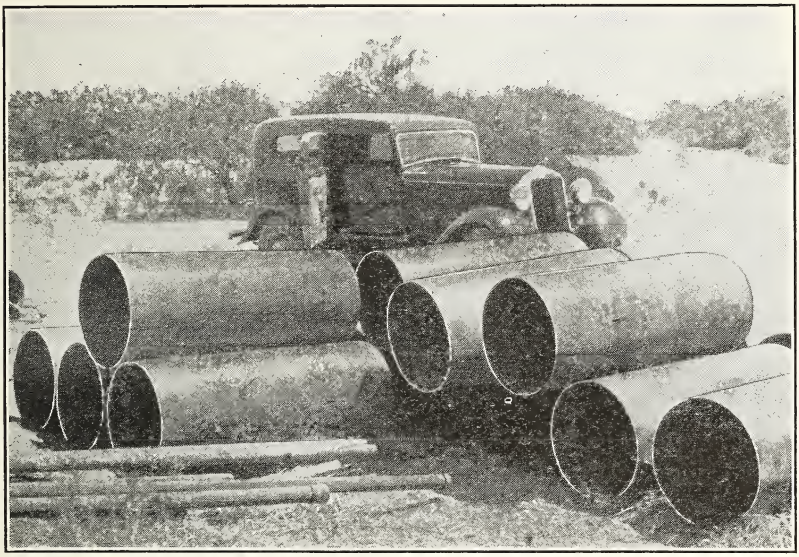

FIGURE 22.—Red iron stovepipe casing in sections 20 inches in diameter and 4 feet long.

on the shoe. This method, however, is usually not satisfactory because it is difficult to keep the well straight and plumb without the starter.

Single-thickness casing with telescope joints or with butt joints and bands is sometimes adopted for shallow wells. This type of casing cannot be used successfully when heavy driving is required because the casing will crumple when subjected to pressure from the jacks or other driving device. Well casing and standard pipe are utilized also for casing when drilling by the California method. A drive shoe is screwed, riveted, or welded to the bottom of the casing. This casing will stand heavy driving, but ordinarily it is too expensive for use unless it can be purchased second-hand. It will stand long periods of drilling with standard tools without injury, and has the added advantage that it can be pulled and used again if necessary.

PERFORATING CASING

The casing is ordinarily perforated in place, although more satisfactory results can usually be obtained when it is perforated before it is placed in the well if the locations of the water-bearing strata are definitely known. There are various methods of perforating casing in place, but the Mill's knife which cuts rings of vertical slots in the pipe at the points desired is most often used.

The Mill's knife (fig. 23) consists of a frame that carries the perforating knife, a string of pipe for pulling the lever that forces the knife through the casing and a cable for holding the perforator in place. This device has an indicator on the pipe which shows where the perforations are being made. The star perforator is also used to some extent. It makes the perforations by means of four star-shaped cutters held in a frame which is forced down by means of a special hammer on the end of a drill stem. The star perforator does not have an indicator to show where the slots are being made. Casing is also perforated by ripping long slots in it with a device called a ripper. These long slots weaken the casing and may cause it to collapse. In perforating casing the Mill's knife starts at the bottom of the well and works toward the top. The other devices start at the top and work down. If there is much sand coming into the well as the result of perforating the casing, the accumulation of sand in the bottom of the well will interfere with the operation of the devices which have to be driven downward. Another type of perforator developed more recently is operated by hydraulic pressure through pistons that cut shutter-shaped perforations in the casing. Like the Mill's knife, the position of this perforator can be accurately controlled, and very satisfactory results are claimed for it.

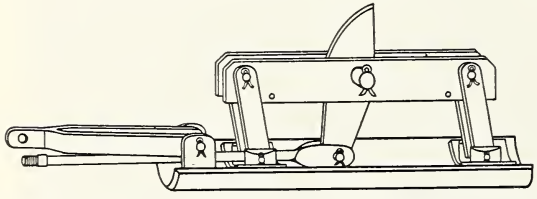

FIGURE 23.—Mill's knife used in perforating stovepipe casing.

The number and size of the perforations required in a well cannot be accurately determined. There should be enough perforations to enable the water to enter the well without unnecessary loss in head and not enough perforations to weaken the casing seriously. Slots from 3 to 6 inches apart around the circumference of the casing and from 5 inches to 1 foot apart along the axis have given satisfactory results under most conditions (fig. 24).

Only the portions of the casing opposite water-bearing formations should be perforated. The location of these formations is obtained from the well log which is determined by the samples of material brought up by the mud scow. Very reliable samples are obtained in this manner because the mud scow picks up the material in the hole as soon as it is broken loose, and consequently the nature of the formations can be more accurately determined.

When the casing is perforated before it is installed in the well, a different type of perforation is used than when it is perforated in place. Both the inside and the outside section of pipe have to be perforated, and in order to have the two sets of holes coincide when the sections are forced together one section is perforated with slots and the other with round holes (fig. 25). When the casing is assembled the lines of the slots and holes are made to coincide, and then when the sections of casing are forced together, the round holes will come under the slots whether the joints come exactly in the center of the sections or not. By using casing perforated before it is installed, the condition of the perforations is definitely known, and there is no possibility that the casing will be insufficiently perforated as frequently happens when it is perforated in the well.

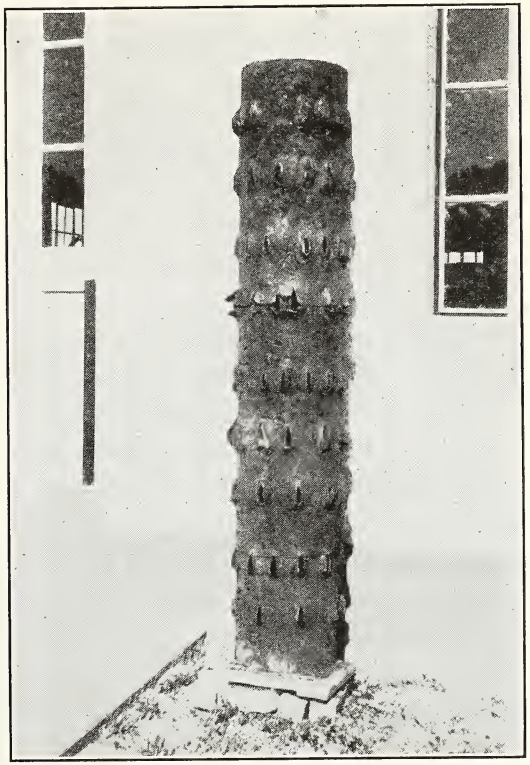

FIGURE 24.—Section of stovepipe casing perforated with Mill's knife.

ADAPTABILITY OF CALIFORNIA METHOD

Most irrigation wells in use at the present time were drilled by the California or stovepipe method. This is not entirely the result of the superiority of this method for drilling wells under all conditions, but is caused by the fact that over 80 percent of all irrigation wells in the United States are in California where conditions are favorable for the use of this method. For drilling relatively deep wells in unconsolidated material the California method has demonstrated its superiority. When the conditions are such that shallow wells only can be obtained, other methods of drilling will be found to be more economical to use and just as satisfactory. This method can be used with standard drilling equipment.

The heavy equipment necessary and the special knowledge required make the California method unsatisfactory for use by the farmer. Wells drilled by this method are expensive, and for this reason the farmer should obtain the services of an experienced and competent well driller rather than attempt to do the work himself.

SAND PUMP AND ORANGE-PEEL-BUCKET DRILLING METHODS

When the water-bearing formations are at a shallow depth and are not covered by a layer of consolidated material or interspersed by layers of clay, boulders, or rocks, the use of some type of bailer, sand-pump, or orange-peel bucket is an effective method of putting down irrigation wells. When this method is used, an open pit is dug by hand or bored with an earth auger down to the water level or to sand in case it is encountered before the water table is reached. Some type of sectional casing is then installed and from then on the well is put down by removing the material from the hole by means of a sand bailer or an orange-peel bucket operated by a portable well-

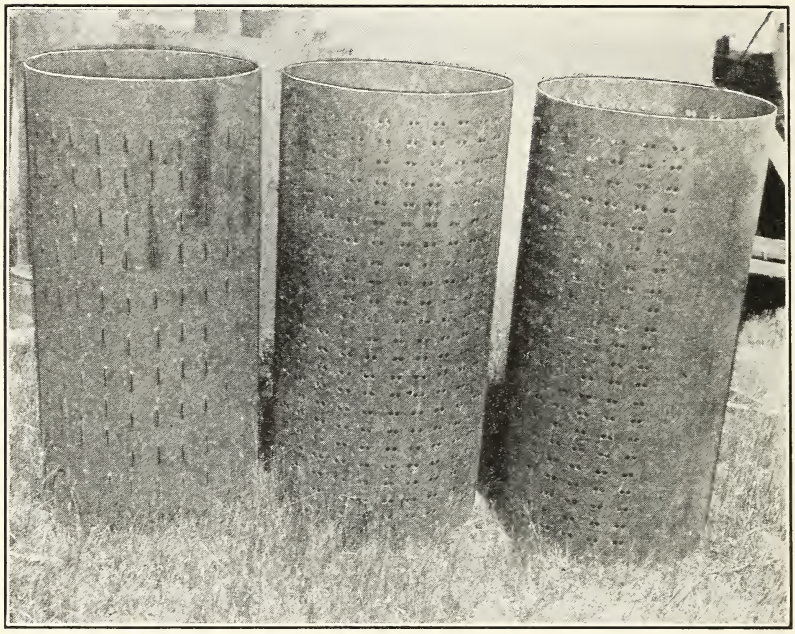

FIGURE 25.—Perforated double stovepipe casings. Outside sections have slotted perforations, and inside sections have double rows of round holes.

drilling rig (fig. 26 (p. 49), an engine driven hoist, and tripod or derrick, or by any other means available. Trucks, tractors, automobiles, or teams of horses hitched to a wire cable or manila rope, which is run through the crown pulley on a tripod set over the well and attached to the bailer or sand bucket, have been used in place of the portable well-drilling rig or engine hoist to operate the equipment. In fact, many successful wells have been put down by these simple means.

As the excavation of the well proceeds the casing is forced down by levers, by weights placed in special boxes hung around the top of the casing or on a platform on top of the casing, by a powerful winch attached to deadmen on each side of the well, or by hydraulic jacks, although the last method is seldom used. If a layer of clay is encountered in the water-bearing formation, it is usually possible

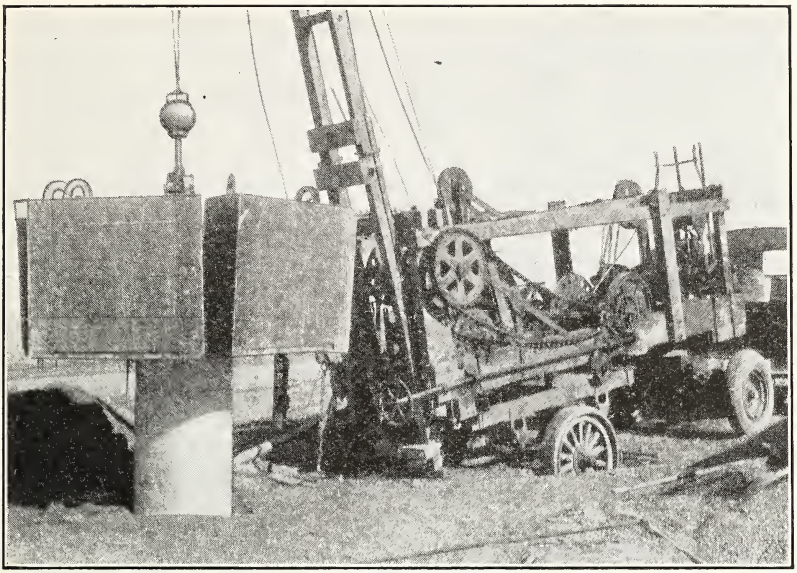

FIGURE 26.—Drilling shallow well with standard portable rig and orange-peel bucket. Galvanized-iron casing is being forced down by means of boxes loaded with sand. Gravel for the gravel envelope is shown at the right of the rig.

to cut through it with the bailer or the orange-peel bucket, but this is a slow process. Under these circumstances it is customary to bore through the layer of clay with an earth auger or to chop it up with a sharp cutting edge welded across the bottom of the bailer. The hole cut by these means is usually smaller than the diameter of the casing. This frequently stops the progress of the casing, and in order to proceed with the construction of the well it is necessary to put a new string of casing inside the first small enough to go through the hole cut in the clay.

TOOLS AND EQUIPMENT

The bailers used when drilling wells by this method are similar to those employed when removing drillings from wells drilled by means of standard tools (fig. 17) except that they are shorter in length. Both plain sand buckets and vacuum- or piston-type bailers are used, depending on the preference of the driller. It is believed, however, that faster drilling would result if the piston type of bucket were more generally used. The ordinary sand buckets are operated on the drilling line of the rig and are churned up and down until the bucket is filled. Piston buckets are operated on the sand line or the drilling line, whichever most nearly meets the conditions as to the power required to hoist the bucket. The piston bucket is filled after being lowered to the bottom of the well by pulling up the piston as rapidly as possible without lifting the bucket off the bottom of the well. Three or four trips of the piston are usually required to fill the bucket. Where sand is encountered above the water table, it is necessary to

supply water as neither the common bailer nor the piston bucket will work in a dry hole.

The orange-peel bucket (fig. 27) will operate equally well in dry or wet sand. It consists of four segments hinged on the top edge and arranged so that when the segments are pulled together they form a hemispherical bucket. The orange-peel bucket is usually operated by two lines, one attached to its frame and one to the mechanism which closes the bucket. When the bucket is lowered, the line to the closing mechanism is kept loose so that the bucket will stand open. When the bucket strikes the bottom of the well, the line on the former is released and the line to the closing mechanism is tightened by the hoist on the rig. This closes the bucket and causes the segments to bite into the sand thereby filling it. The bucket is then hoisted by the same line. To dump it, the line to the frame of the bucket is tightened, and the line to the closing mechanism released.

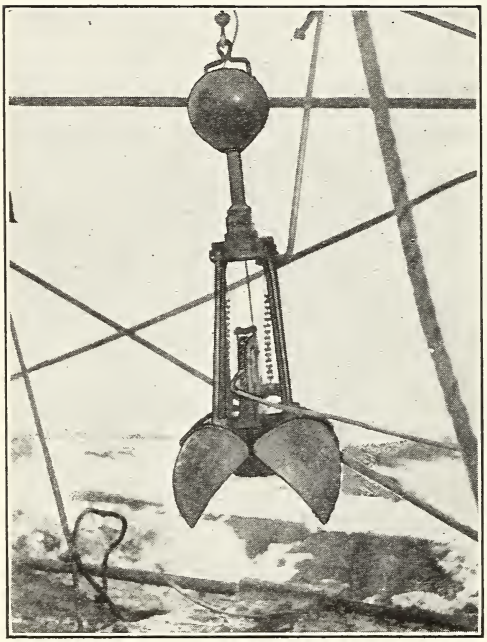

FIGURE 27.—Orange-peel bucket with ball weight operated by means of a single line. Bucket is dumped by hanging it on hook as shown.

The orange-peel bucket can be operated by means of a single line attached to the closing mechanism, if necessary, as is the case when only a single drum hoist, a truck, or similar equipment is available for operating the bucket. To do this, a short auxiliary line with a hook at one end is attached to the hoisting cable above the bucket. When lowering the bucket the hook is attached to the frame; this takes the pull off the closing mechanism and allows the bucket to open. When the bucket strikes the bottom of the well the auxiliary line slackens and unhooks. This action permits the hoisting line to function, closing the bucket when it is pulled up. To dump it a short rod with a hook at one end, which is attached to the derrick, is hooked into the frame of the bucket. When the hoisting line is slacked off, the pull on the closing mechanism is released, and the bucket opens.

Some orange-peel buckets are equipped with a heavy ball weight which slides on a rod attached to the frame. When the bucket is dropped into the well the ball drives the points of the bucket into the sand by dropping upon the frame when the hoisting line becomes slack. The ball or hammer type of orange-peel bucket is especially effective when digging in clay or hard sand.

The most common method of forcing the casing down is by loading a wood platform on top of the casing with the material excavated from the well. This works satisfactorily, but has the disadvantage that it is necessary to unload the platform each time a section of casing is added. An improvement is to hang containers for the sand from the top of the casing. When it is necessary to add another section of casing the sand-filled containers are removed by attaching them to the hoisting line. The containers should not be too large as they are difficult to handle. Old oil drums make satisfactory containers. A method sometimes used when sinking large casings is to dump the excavated material back into the casing on a floor built in the bottom of the casing. A hole just large enough for the bailer is left in the floor, and an auxiliary casing is set therein to keep out the material dumped back into the hole. As the depth of the hole increases the weight of material forcing the casing down increases. When the well is completed the material in the large casing is taken out with the bailer or sand pump. This method is satisfactory for sinking large casings in sand formations, but it cannot be used succesfully if layers of clay or consolidated material are encountered.

Levers or pries are often used to force down the casing. These levers are made of a pair of beams from 16 to 24 feet long braced together so as to form a rigid unit with space enough between them to allow the casing to pass through. One end of the lever is placed under the frame of the rig or attached to deadmen buried near the well as a fulcrum. The other end is loaded with sand or other material. The pull-down ears or pull-down head on the casing is attached to the lever by a pair of chains or similar means at a point near the fulcrum. With this equipment it is possible to exert a force of several tons on the casing, which is ample for most conditions.

Another method of forcing the casing down is to use a winch having a very small drum which is operated by a long lever and ratchet. The winch is firmly anchored to deadmen buried near the well. The cables from the winch are run over pulleys attached to the pull-down head on top of the casing and then back to the frame of the winch. By turning the drum with the lever the cables are tightened and the casing is forced down. This is a simple method of forcing the casing down, but more time is required to set up the apparatus than is necessary when the other methods are used, because pits have to be dug to bury the deadmen.

If the casing stops going down, it can usually be started by allowing the bailer or orange-peel bucket to fall into the well from the top of the derrick. The jar caused by the heavy equipment striking the water surface is sufficient to break the casing loose. If the casing gets caught on a rock, the usual practice is to shatter the rock with dynamite, but before doing this it is necessary to withdraw the casing far enough so that it will not be injured by the explosion.

CASING

Several different types of casing are used in wells put down by means of bailers or orange-peel buckets. Of these the riveted casing composed of rolled sheets of either black or galvanized iron is in most common use. The vertical joints in the sections are lap-riveted or

butt-welded. This casing is made in sections from 24 to 36 inches in length and from 6 to 48 inches in diameter. The thickness of the material depends on the depth of the well and the diameter of the casing. The minimum gages recommended by Code (5) for various depths and diameters are given in table 2. Large casing of this type is usually reinforced by bands at the joints in addition to being made of heavier material. This type of casing is comparatively cheap; it is easy to install and may be purchased from local dealers. If the casing is galvanized, it will last a long time in ordinary soils.

TABLE 2.—*Recommended minimum well-casing thickness for shallow wells, United States standard gage* (5)

Depth of well (feet)	Thickness for diameter of well casing of—												
	8 inches	10 inches	12 inches	14 inches	16 inches	18 inches	20 inches	24 inches	26 inches	30 inches	36 inches	42 inches[1]	48 inches[1]
	Gage	*Gage*	*Gage*	*Gage*	*Gage*	*Gage*	*Gage*	*Gage*	*Gage*	*Gage*	*Gage*	*Gage*	*Gage*
20	16	16	16	16	16	16	14	14	14	12	10	16	16
30	16	16	16	16	16	14	14	14	14	12	10	16	14
40	16	16	16	16	14	14	14	14	12	12	10	14	14
50	16	16	16	14	14	14	14	12	12	12	10	14	14
60	16	16	14	14	14	14	14	12	12	10	10	12	12
70	16	14	14	14	14	14	12	12	10	10	10	12	12
80	14	14	14	14	14	12	12	10	10	10	10	12	12
90	14	14	14	14	12	12	12	10	10	10	10	12	-------
100	14	14	14	14	12	12	10	10	10	10	10	-------	-------

[1] Reinforcing bands of following sizes placed on outside of casing at top and bottom and at joints also on diameters greater than 36 inches: 1 by ¼ inch on 8- and 10-inch wells, 1½ by ⅜ inch on 12- to 18-inch wells, 2 by ⅜ inch on 20-inch wells, 3 by ⅜ inch on 24- to 36-inch wells, and 3 by ½ inch on 42- and 48-inch wells.

Another type of casing used in wells excavated in this manner consists of either plain or reinforced concrete rings, (fig. 11) which are made with tongue-and-groove joints or have vertical holes in them through which rods or cables are strung which hold the casing together. Tie plates which extend across the joints and are bolted to the adjoining sections are sometimes used to hold the sections together. These rings are usually built on the ground, but are sometimes cast in the well, section by section, as the well is excavated. This type of casing is generally used in the larger sizes of wells. The thickness of the walls of the rings is from 4 to 6 inches. Concrete casing can be used under most conditions where metal casing is satisfactory and in addition can be used where the soil or the water corrodes metal. Certain waters, however, cause deposits to form on concrete. Where this occurs metal casing gives better results.

Wood casing is sometimes used in the larger wells of this type. The casing is built in sections and consists of wood staves which are either held in shape by metal hoops or by circular frames built up of planks. Wood casing is usually made with the staves flatwise, but it is also made with the staves on edge as shown in figure 28, which makes the stronger casing. Wood casing is not satisfactory where it is alternately wet and dry, and for this reason it should not be used above the low-water line. Brick or concrete curbs should be used above the water line. They also provide additional weight for forcing the casing down.

PERFORATIONS

Shallow wells require a large area of perforations per unit length of strainer to let the water in because the depth of water in the well is small, consequently only a short length of strainer can be employed. In order to get the water through the strainer without an unduly large loss of head, a large area of perforations has to be

FIGURE 28.—Built-up wood casing 6 feet in diameter and 32 feet long which was put down successfully in a sand and gravel formation by means of a sand bucket. The sand was bailed out through a hole in the floor in the bottom of the casing and then dumped on the floor to furnish the weight to force the casing down. The sand was bailed out after the casing had reached the desired depth.

provided. Metal casing is well adapted for this purpose because the slots can be placed close together, and unless the sand is too fine the size of the perforations can be made large enough to permit the water to enter freely. Perforations in metal casing are made with various shapes, but the chisel type of perforation (fig. 29) is the

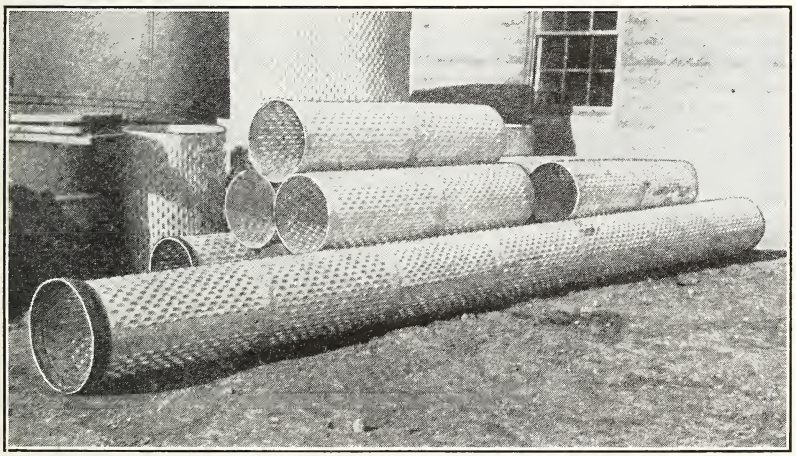

FIGURE 29.—Galvanized-iron casing perforated with chisel slots.

most common. It consists of a slot cut through the casing from the inside by means of a chisel punch. This method leaves the opening larger on the inside, and tends to keep the holes from clogging with sand. Chisel-type perforations are made from one-sixteenth to three-sixteenths of an inch wide, are usually about 1 inch long and are spaced from ¾ to 1½ inches apart. The width of the perforations is determined by the depth of penetration of the punch. There are minor variations in the shapes of the perforations made by this method, but the essential features are the same. One type for which important advantages are claimed is made with a punch having round ends. Perforations made by this method have rounded ends that strengthen the casing at this point.

Another form of perforation of this type consists of raised strips (fig. 30) with the holes for the entrance of the water at the sides

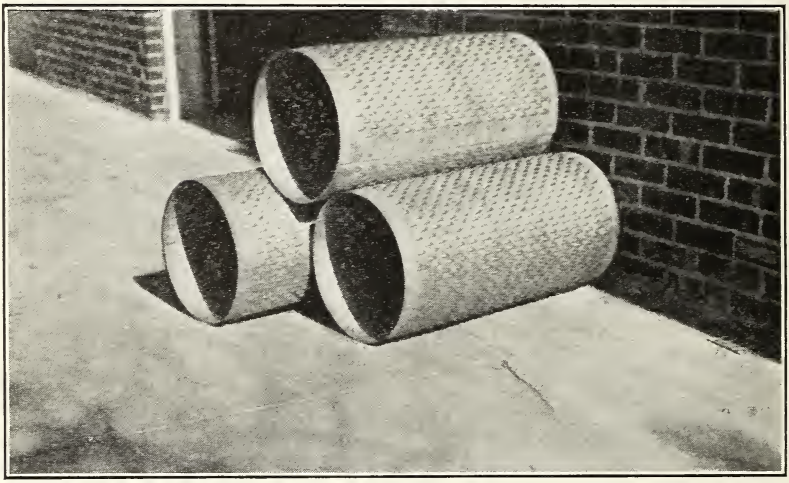

FIGURE 30.—Galvanized-iron casing with lattice perforations.

of the strips. These perforations are made by a punch which cuts the strips and then pushes them out the amount necessary to give the size of opening desired at the sides. Still another type of metal casing has the perforations in the form of horizontal louvers (fig. 31) having the opening on the bottom. It is claimed that sand does not enter the perforations in this casing readily because the opening is protected by the hood. This is the type of perforation used in heavy-gage casing. Still another form of perforation used in metal casing is the crowfoot type (fig. 32). It is similar to the casing shown in figure 30 except that the strips are cut in a pattern roughly resembling a crowfoot. These various forms of perforations are usually made in flat sheets by power-operated punches and afterwards rolled to form the casing.

A type of perforated casing sometimes used in fine materials is similar to a sand point except that it is much larger. It consists of a standard pipe or well casing through which ⅝-inch holes have been drilled and then covered with a 12- or 14-mesh brass screen as shown in figure 33. The brass screen is protected by a sheath of

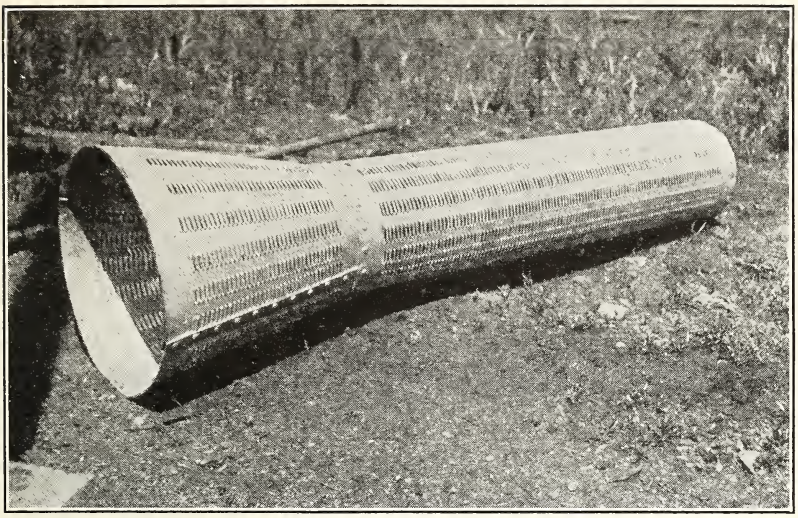

FIGURE 31.—Heavy iron casing with shutter perforation for use in gravel-envelope wells.

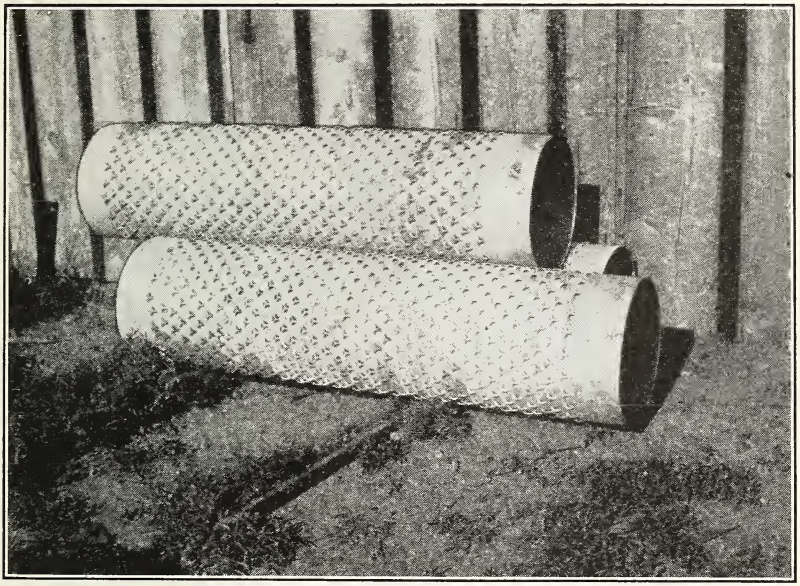

FIGURE 32.—Galvanized-iron casing with crowfoot perforations.

¼-in mesh galvanized-iron hardware cloth. This casing is expensive, but it is effective in keeping out fine sand. Special provision has to be made for its installation because it cannot stand driving without injury. This strainer is usually set in a blank casing that has previously been sunk to the desired depth in the water-bearing formation. The blank casing is then pulled, and the space between the wall and the strainer filled with suitable gravel. This type of casing is also used in wells put down by the hydraulic rotary method (p. 57) without the use of blank casing.

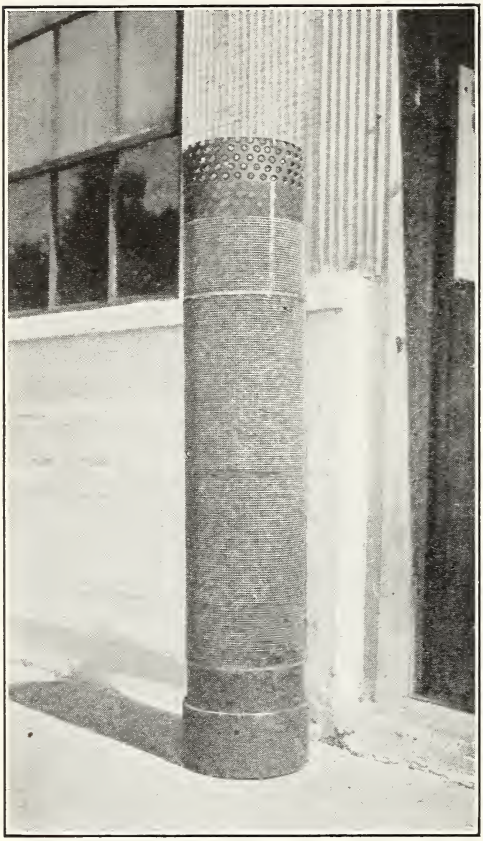

FIGURE 33.—Perforated casing covered with fine screen for use in irrigation wells in fine sand.

The perforations in concrete casing are in the form of slots cast in the rings by inserting wood or metal wedges which are subsequently removed. Figure 34 shows a patented concrete casing having vertical slots that are connected to passageways in the concrete. A much greater area of perforations is obtained by this method than is usually found in concrete casing. The latter form of concrete casing is used most extensively in city wells for domestic water supplies because the higher first cost of this casing is not such an important item in the entire cost of city water supply.

The perforations or openings in wood casing are made by laying the staves (fig. 28) so that there are vertical spaces between them. These spaces are usually wider on the outside than on the inside but sometimes the edges of the staves are so planed that the slots are narrowest on the outside. The width of the slots can be varied to suit the size of the sand in the water-bearing formation, but in doing this consideration should be given to the fact that the lumber will swell in the water.

ADAPTABILITY OF THE SAND-PUMP OR ORANGE-PEEL-BUCKET METHOD

Farmers using the sand-pump or orange-peel-bucket method have in many instances obtained successful wells. They should not, how-

ever, attempt to put down wells by this method if layers of clay or beds of boulders are likely to be penetrated. Under these conditions an experienced well driller should be hired to do the work.

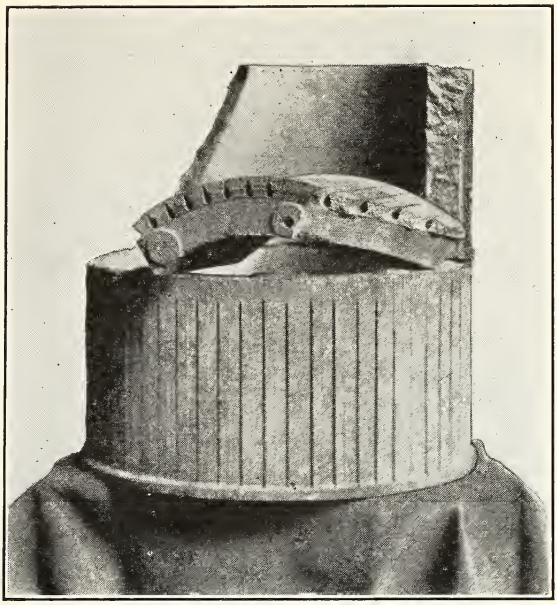

FIGURE 34.—Patented concrete casing with slotted perforations. Rings are held together by cable threaded through holes in concrete.

HYDRAULIC-ROTARY METHOD

The hydraulic-rotary method is especially adapted to drilling irrigation wells up to 18 inches in diameter in unconsolidated materials, and, by using a reamer, even larger wells can be put down. It is an effective method where layers of clay are encountered which frequently cause considerable delay when using a bailer or an orange-peel bucket. The hydraulic-rotary method is one of the fastest methods of drilling wells. Wells drilled by this process are put down by means of a rotating bit through which a mixture of clay and water is forced at high pressure (figs. 35 and 36). The bit is

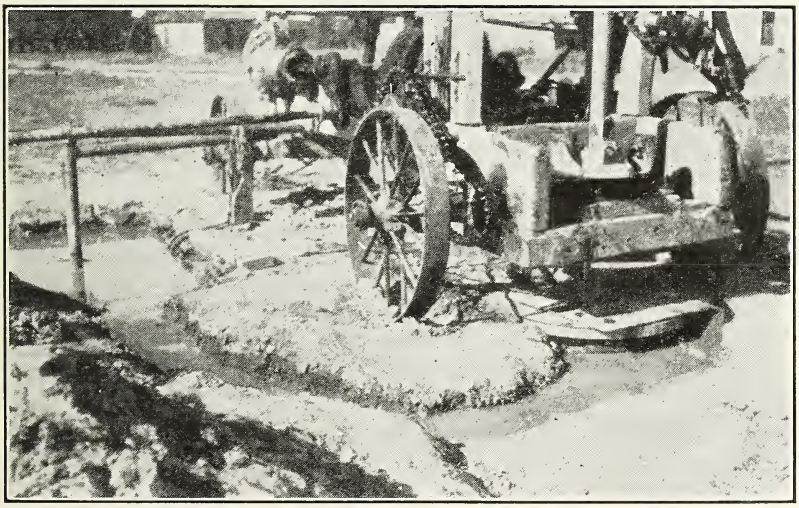

FIGURE 35.—Hydraulic-rotary rig drilling artesian well 17 inches in diameter. Hole is 410 feet deep.

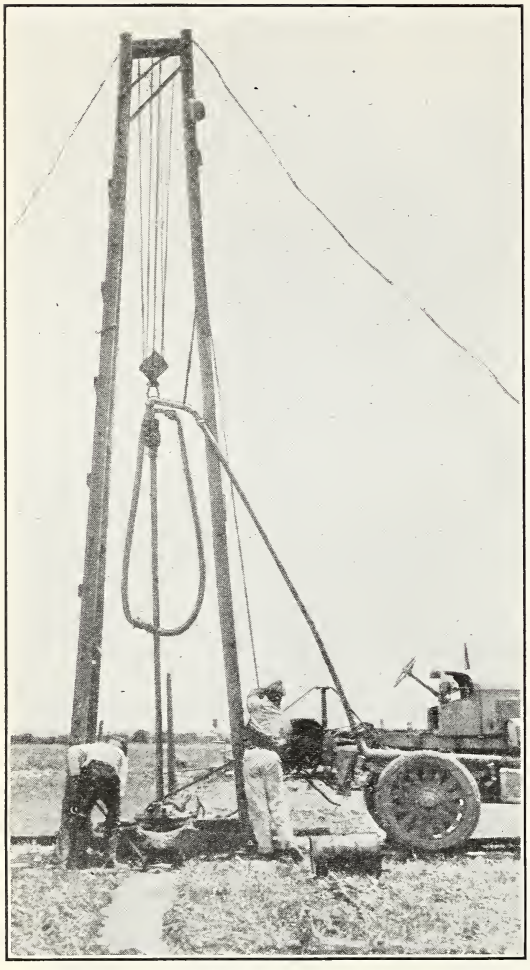

FIGURE 36.—Hydraulic-rotary rig with separate derrick.

attached to a hollow drill stem through which the clay and water mixture is pumped. The material in the hole is loosened by the rotation of the bit and by action of the high-pressure jets from the bit, and the loosened material is carried to the surface by the mixture of clay and water as it flows upward. Some of the clay in the mixture deposits on the sides of the hole, and the rubbing of the drill stem on the deposit forms a substantial clay lining. No casing is ordinarily used while drilling the hole, the clay lining forming a wall sufficiently strong to keep the material from caving. Wells several hundred feet deep have been drilled by this method in unconsolidated formations without casing.

TOOLS AND EQUIPMENT

The drill used in this method is known as the fishtail type (fig. 37, *A*). It has a hollow shank and an orifice on each side for the jet. The bit is attached to a drill stem consisting of heavy pipe which is turned by means of a rotating table through which the drill stem can slide as the hole deepens. The drill stem is connected by a pressure hose with the double-acting plunger pump which forces the mud into the drill stem. The rigs used for rotary-hydraulic drilling are of several types, but all of them have a rotating table, a pair of double-acting plunger pumps, a hoist, and an engine. This is all the equipment some drillers use except a derrick built over the well. Most rigs, however, have standard drilling equipment in addition to the special attachments necessary for rotary drilling. This makes it possible to drill with standard tools or to use the rotary bit for percussion drilling in case a layer of hard material is encountered.

Duplicate pumps and swivel hose connections are usually provided so that there need be no delay caused by repairing one of the pumps nor by changing the hose connection when adding another length of pipe to the drill.

After the mixture of water and clay with its load of drillings reaches the surface, it is run into a sump through a channel long enough to permit the sand and chips in the drillings to be deposited before they reach the sump (fig. 35.) From the sump the mixture of clay and water is taken into the pump through a suction hose and again forced down the drill stem and out through the openings in the bit. From time to time more water and clay have to be added to take care of seepage and the material lost in mudding up the sides of the hole.

It is claimed that, when using the hydraulic method, the driller may pass a water-bearing formation without noticing it. However, an experienced driller will know whether he is drilling through a water-bearing formation or not. In the first place, layers of sand below the water table usually contain water, and secondly, the pressure on the mud pump usually drops when a water-bearing formation is encountered because the water in the mud mixture escapes more rapidly in such a formation than in an impervious layer. The escape of the water causes the pressure on the mud pump to drop, and as most pumps are equipped with pressure gages, the driller has a good indication that he is passing through a water-bearing formation. If the water in the formation is under considerable pressure, the change in pressure may be too small to be detected on the gage. For this reason best results are obtained by this method when the log of the formations and the location of the water-bearing strata in the area are known from previous tests.

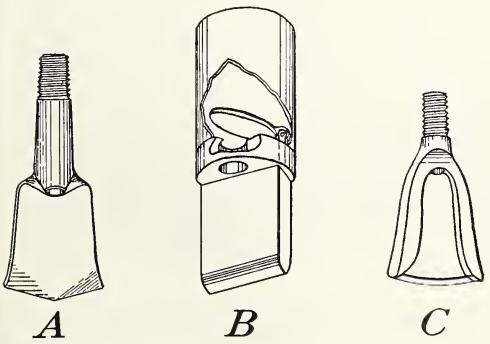

FIGURE 37.—Types of bits used with following equipment: *A*, Hydraulic-rotary; *B*, hollow-rod; *C*, jetting.

When the hole is drilled to the depth desired, the drill is withdrawn and the casing with perforations opposite the water-bearing formations is lowered into the hole. The well is then backwashed to remove the clay that has deposited on the wall of the hole and sealed the water-bearing layers. This is done by lowering the drill to the bottom of the well and then forcing clear water through the bit by means of the pressure pump. A collar that fits the casing is attached to the drill stem just above the bit so that the water will be forced out of the casing and against the mud wall of the well. Plunging the drill with the attached collar rapidly up and down in the casing opposite the area being washed is very effective in loosening the clay deposits. As soon as the clay is washed away in one portion of the

well, the equipment is raised so that a new area will be exposed to the action of the water.

In order to concentrate the flow of water from the pump in a limited area, two diaphragms or collars, one above and one below the jets, are sometimes used. By reducing the distance between the diaphragms, the area being washed at one time can be reduced to any desired limit. The clay washed off the wall of the hole mixes with the water pumped in and is carried to the surface on the outside of the casing. While the washing is in progress, screened gravel, usually pea size, is slowly shoveled into the space between the casing and the wall of the well to form a gravel screen to replace the clay washed out, and to fill cavities developed by the drilling process. As soon as possible after the washing process is completed the well should be pumped in order to take out any clay remaining in the gravel or the surrounding sand before it has a chance to settle and seal the pores in the material surrounding the strainer.

There is some uncertainty as to whether it is possible to wash the clay out of the water-bearing strata after they have once been sealed by this method of drilling, and for this reason when the water-bearing formation is reached the hydraulic-rotary process is often discontinued, and the hole completed by sinking the strainer by means of a bailer. This practice eliminates the possibility of clogging the water-bearing formation with clay. Where the water-bearing material is fine, pea-size gravel should be fed outside the strainer as the hole is deepened in order to replace material pumped out and to provide a gravel screen or envelope for the well.

CASING

The casing used in wells put down by the hydraulic-rotary process varies in different parts of the West. In some areas the California stovepipe or double casing is used. The sections of casing have to be welded or riveted together because the casing is set after the hole is completed. This casing is usually assembled in 20-foot lengths at the factory, and these sections are joined together when they are lowered into the well. Well casing joined together by threaded couplings or welded joints is used also. In other areas riveted sheet-metal casing of only one thickness is used. This type of casing is made with telescope joints or butt joints and, like the stovepipe casing, is built in sections about 20 feet long at the factory. The sections are joined together when they are placed in the well. Heavy-gage materials are used in making the casing for wells put down by this process. Lightweight galvanized casing, such as used in shallow wells put down by means of bailers or orange-peel buckets, is seldom installed. Sometimes one kind of casing is used above the water-bearing formation and another for the perforated portion in the zone from which the water is to be drawn.

PERFORATIONS

The log of the well is known before the casing is set, so there is no advantage in using casing that has to be perforated after it is in place. Hence when perforated casing is installed in wells put down by the hydraulic-rotary process, the factory-perforated type is generally used. The type of perforations most often used in stovepipe

casing consists of round holes and slots (fig. 25), as described on page 47. Single-thickness casing is made with chisel-punch, horizontal-louver, crowfoot, or other special-shape perforations. Standard well casing is perforated with slots cut with an acetylene torch (fig. 38). The sizes of the perforations, for wells made by the

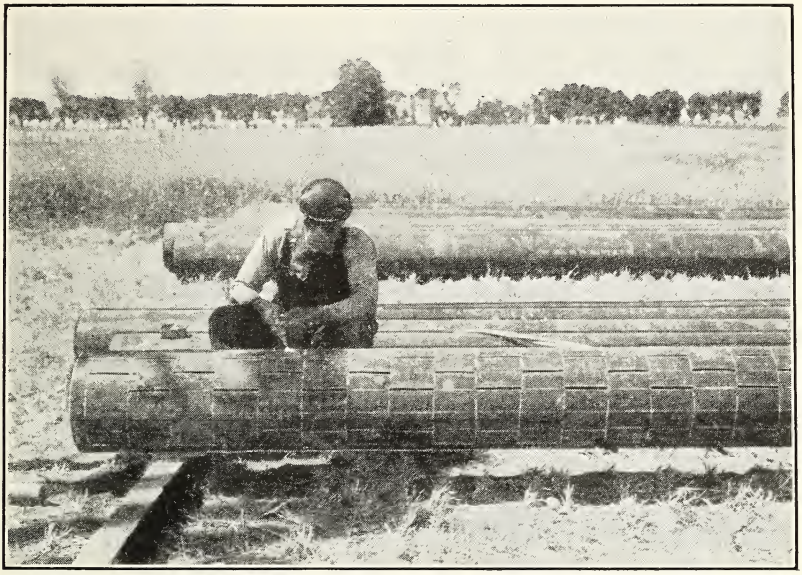

FIGURE 38.—Perforating 14-inch well casing with acetylene torch. The sections of casing are welded together as they are put into the well.

hydraulic-rotary method, are the same as those used in wells put down by other methods in similar materials. In very fine material special types of strainers must be used. The strainer, consisting of standard pipe or well casing perforated by $\frac{5}{8}$-inch bored holes and then wrapped with 12- or 14-mesh brass-wire screen and $\frac{1}{4}$-inch mesh hardware cloth (fig. 33), has been used successfully. Another strainer used under these conditions is made by wrapping a trapezoidal-shaped brass band around a perforated pipe similar to that just described. The width of the slots formed, which is determined by the spacing of the bands, is fixed permanently by punching lugs on the bands after they are wound around the perforated pipe. The bands are wound on the pipe so that the wide portion of the band is on the outside. This arrangement makes the slots wider on the inside than on the outside and helps to keep the sand particles from clogging the perforations. This screen works very satisfactorily in fine sand, but it is more expensive than the other types.

ADAPTABILITY OF THE HYDRAULIC-ROTARY METHOD

The construction of irrigation wells by the hydraulic-rotary process requires special machinery and a driller familiar with this method of drilling because of the skill required in getting an accurate log of the material passed through and in washing the clay from the wall of the hole after the well is completed.

GRAVEL-ENVELOPE OR GRAVEL-SCREEN WELLS

The gravel envelope or gravel screen used in irrigation wells is an auxiliary strainer that has been developed in recent years for keeping fine sand from coming into the well and reducing the resistance to the flow of the water through the material surrounding the well. It also fills the cavities that occur. The gravel envelope consists of a layer of screened gravel which surrounds the casing. The thickness of the layer is normally from 6 to 12 inches but is probably much greater where the casing passes through a bed of fine sand that can be carried through the perforations in the casing, and much less where the casing passes through a layer of clay. Gravel envelopes are used on wells put down by means of a bailer or sand pump, on wells drilled with standard tools, and on wells drilled with a mud scow or by the hydraulic-rotary process.

There are two methods of making gravel-envelope wells. In one method the gravel is placed around the casing after the hole for the well is completed. In the other the gravel envelope is put in at the same time the well is being drilled. When the first method is used either a blank casing is sunk to the desired depth or a hole is put down by the hydraulic-rotary process in which a clay lining is built up on the inside of the hole. After the hole is completed, the casing, with the perforations located so that they will come opposite the water-bearing formations, is lowered into the well. In wells with blank casing, gravel is then filled into the space between the blank casing and the perforated pipe. As the filling proceeds the blank casing is withdrawn. When a gravel envelope is used in connection with a well drilled by the hydraulic-rotary process, the gravel is added after the perforated casing has been installed and while the clay deposit is being washed from the walls of the well. The gravel fills the space between the casing and the sides of the hole and prevents the wall of the well from caving when the clay lining has been washed off.

When the gravel envelope is put in at the same time that the well is being drilled, the usual practice in shallow wells is to excavate the well down to the level of the water somewhat larger in diameter than the casing which is to be used. The casing is set in this hole and the space between the casing and the sides of the hole is filled with gravel. As the sinking of the well proceeds some sand is pulled into the well through the perforations and under the bottom of the casing. This material is replaced by the gravel which works down as the casing sinks. As the level of the gravel around the casing is lowered more gravel is added.

Another method which is used when drilling deep wells where the water table is at a considerable distance below the surface, is to drill several holes near the well at such an angle that they will intersect the bore of the well at about the water surface. Then as the drilling proceeds gravel is fed into these holes, and as the sand around the casing flows into the well it is replaced by gravel that comes down through the holes around the well. Either method of getting the gravel to the water level is satisfactory, although the first method is used most often.

The amount of gravel required varies from a few yards to several hundred, depending on the diameter, the depth, and the nature of the formations penetrated. In drilling through some fine-sand formations a large quantity of sand is carried into the well. When a gravel envelope is used, the material taken out is replaced by gravel, and the danger of a cave-in which might cause the failure of the well is avoided.

A gravel envelope provides a continuous passage for the water from one water-bearing formation to another, and if it should happen that the casing opposite one of these strata was not perforated, the water from the formation would flow through the gravel screen to the perforated portion of the pipe.

The use of excessive quantities of gravel may indicate that the casing is not being forced down rapidly enough, thereby permitting a large quantity of sand and gravel to come into the well under the casing. If this condition is permitted to continue, some of the water-bearing formations may become distorted and even shut off completely by overlying beds of clay. For this reason the casing should be forced down more rapidly when this condition exists.

The blank casing, sometimes put down in making gravel-envelope wells, may be left in place if the water-bearing formations are fine or if there is danger of caving. In the event the casing is left in the well, it is perforated in place opposite the water-bearing formations. The inner casing is perforated before it is put into the well. The space between the inner and outer casing is then filled with screened gravel. This method of construction is more expensive than when a single string of perforated casing is used, but the use of this method provides another safeguard against the danger of caving, the possible failure of the well, and injury to the pump. It should be mentioned, however, that when the gravel is confined between the two strings of casing, the permeability of the gravel frequently decreases rapidly owing to clogging of the pore spaces (*36, p. 404*).

In making gravel-screen wells the type of gravel used should be given careful consideration. The principal purpose of the gravel screen is to keep fine sand from coming into the well and to provide an easy passage for the water as it approaches the strainer. If the water-bearing material is coarse gravel, no great advantage will probably result from the installation of a gravel screen, because the fine material will be washed out of the coarse gravel by pumping and the latter will be left, which makes just as effective a screen as any that may be produced by adding more gravel. Screened pea-size gravel has been found to be most satisfactory for the conditions usually encountered. Mixtures of gravel of various sizes are unsatisfactory, because the smaller particles fill the spaces between the larger ones and cut down the pore space, which increases the resistance to the passage of the water. The greater the thickness of the gravel screen the more effective it is in holding back fine sand, because the velocity of the water through the sand decreases as the distance from the strainer increases because of the greater area of the section through which the water must pass. The velocity decreases at about the same rate as the diameter increases, and, since the weight of particles which can be carried along by the current varies as the sixth power of the velocity, it is obvious that cutting the velocity in half will reduce mate-

rially the weight of the particles of sand that can be moved. It is evident from the foregoing that, if the diameter of the sand screen were increased sufficiently, the velocity could be reduced to a point where it would no longer wash out the sand regardless of how fine it was.

DEVELOPMENT OF WELLS

The purpose of developing wells is primarily to increase the yield at a given draw-down, or in other words, to reduce the draw-down when pumping a definite quantity of water. This result is accomplished by washing the fine sand, silt, and clay out of the water-bearing formation in the area immediately surrounding the perforated portion of the casing. The removal of the fine materials opens up the channels through which the water enters the well, and consequently, reduces the resistance to the flow. Because of this fact, the maximum yield of the well will be increased as will also the yield per foot of draw-down, and, incidently, in doing this the flow of sand into the well will be stopped or at least temporarily reduced.

The development of irrigation wells in many sections has not been given the attention it deserves. The situation is partly due to the fact that both the farmer and the driller are anxious to complete the well, and as a result this important part of the work is neglected or only indifferently done. They should both realize that in order to get the best well possible it is just as important to develop it properly as it is to use the best method in drilling. The yield of a well per foot of draw-down has been more than doubled by thorough development, but such a marked improvement cannot be obtained in every instance (*5, p. 30; 29, p. 146*).

DEVELOPING BY PUMPING

Developing a well by pumping is not so effective as some of the other methods, but it yields very satisfactory results. This process is sometimes known as "rawhiding" the well. The only equipment necessary to develop a well by this process is a pump (fig. 39), preferably a turbine with sufficient capacity to handle the estimated discharge from the well. If electrically driven, the pump should be equipped with a regulating valve for controlling the discharge. A valve is not necessary on engine-driven plants because the discharge of the pump can be controlled by throttling or accelerating the engine. The larger the pump is, the better. A long suction line should be attached to the pump so that it will pick up from the bottom of the well the sand carried in by the process of development. A new pump should not be used because the large quantity of sand which must be pumped will cause considerable wear and might seriously reduce its efficiency. The pump used to develop the well can also be used to test the well.

Before starting the developing process the well should be pumped slowly at first and gradually at higher and higher rates. At each rate the pumping should be continued until no more sand comes into the well. This procedure should be continued until the maximum

capacity of the pump or the well is reached. The pump should not be shut down after starting until this preliminary pumping is completed, because there is danger that, if the sand is not kept moving, it may clog the well or lock the pump. The pump should not be started at maximum capacity because there is a tendency for the sand particles to bridge if the water from the formation is drawn at too high a rate at the start.

After pumping has continued at the maximum rate until the water begins to clear, the pump should be shut down until all the water in it has drained back into the well and the water table has returned approximately to normal. As soon as the water level in the well has built up the desired amount, the pump should be started again and the process repeated. The alternate stopping and starting of the pump stirs up the material surrounding the casing and causes the fine material to come into the well until the passages for the water are cleaned out.

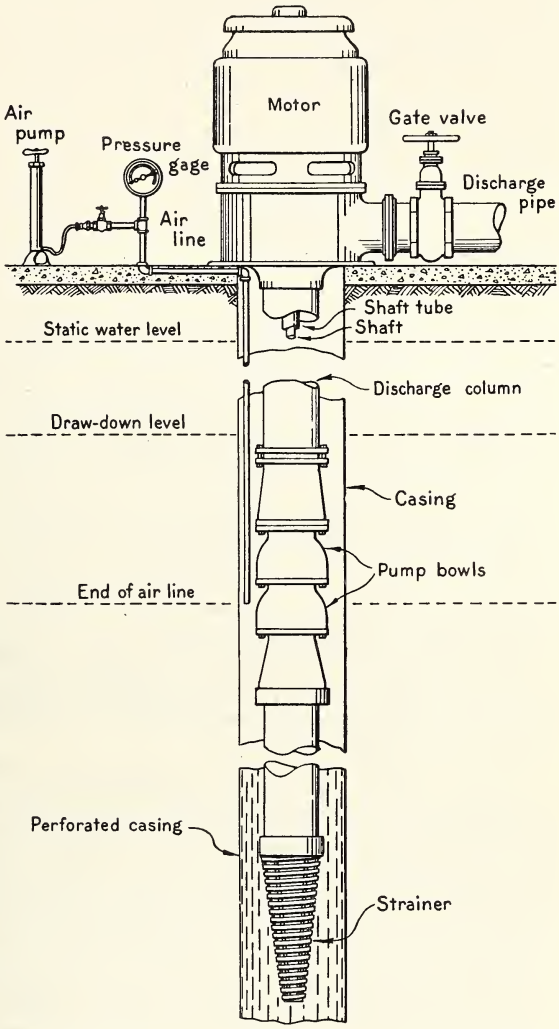

FIGURE 39.—Turbine test pump with air line for measuring draw-down.

The time required to develop a well by this process varies through wide limits. Sometimes only a few hours are required, but usually at least a day is necessary. When no more sand is brought in, the work is complete so far as this method is concerned. If it is thought desirable to continue the development of the well, some other method will have to be adopted.

DEVELOPING BY SURGING

One of the most effective methods of developing wells is by surging. There are several ways of doing this. The essential feature is the rapid up-and-down movement of a plunger in the well opposite the perforations in the strainer. Raising the plunger draws water and fine materials into the well and lowering it forces water out through the perforations and into the material surrounding the strainer. This reversal of flow overcomes the tendency of the sand to bridge and brings in much more fine material than when the flow is always toward the well. The action is more violent and consequently more effective than when the developing is done with a pump.

One of the commonest ways of developing wells by surging is by means of a mud scow. This is well adapted to wells drilled by the California method because the rig and the mud scow necessary for doing the work are available at the site when drilling is completed. The mud scow used for surging should have sufficient clearance so that it will move freely in the casing. The mud scow is attached to the drilling line and is given an up-and-down movement by the walking beam. A long stroke is used, and the speed is adjusted until there is no slack in the cable on the down stroke. The usual practice is to start surging at the top of the perforated portion of the casing and then to work down gradually by playing out more cable. The sand, drawn in by the surging process, accumulates in the bottom of the well and has to be bailed out from time to time. In order to obtain the most effective results, the valve in the mud scow should be closed. This is done by filling the mud scow with gravel or by placing a strut between the valve and the bail of the mud scow. A heavy mud scow should be used so that it will force the water out of the well rapidly on the down stroke.

The mud scow is operated in this manner until no more sand comes into the well. Two or three days are usually required to develop a well by this method. Less time is ordinarily required to develop shallow wells than deep ones.

A sand pump or bailer can also be used for the purpose of developing wells. The bailer, loaded with sand to give it more weight, is operated on the drilling line and is given the up-and-down movement by being attached to the spudding mechanism on the rig. If the rig does not have this equipment, the bailer can be run up and down by means of one of the hoists on the rig. This method, however, is not so satisfactory because the sand-line hoist is usually too light and the drilling-line hoist too slow to get the best results.

Another method of surging a well is to use a surge block (fig. 40). The surge block consists of a circular wood disk several inches in thickness which is attached to a metal stem for the purpose of guiding the plunger and giving it additional weight. The circular disk should not fit tightly in the casing because the block would not drop rapidly enough on the down stroke, nor would it be possible to raise the block fast enough on the upstroke with the power of an ordinary rig, to obtain the best results. When a surge block is used to develop a well cased with lightweight riveted pipe, there is danger that the surge block will tear the casing. In order to elimi-

nate this danger, the disk is wrapped with rubber belting or covered with an old truck tire. The surge block can be operated by the drilling line on a California or a standard rig. A long stroke is used, and the speed is adjusted so that the cable will not become too slack on the down stroke. Some drillers prefer surge blocks equipped with valves so that there will be very little obstruction to the movement of the surge block on the down stroke. This permits faster spudding action and makes possible a faster suction stroke.

The action of the surge block is similar to that of the mud scow. The usual practice is to begin at the top of the perforated section of the casing and work down. The sand drawn in through the perforations accumulate on the bottom of the well and has to be bailed out from time to time. Wells with perforated casing put down by means of a bailer, mud scow, or orange-peel bucket receive considerable development as a result of a similar action of these tools while the well is being drilled. The time required to develop a well with a surge block is about the same as that required when using a mud scow. The surging is discontinued when no more sand comes in. The well is then pumped at the maximum rate for several days. The procedure opens up the water-bearing formation in the area which cannot be reached by the surging process.

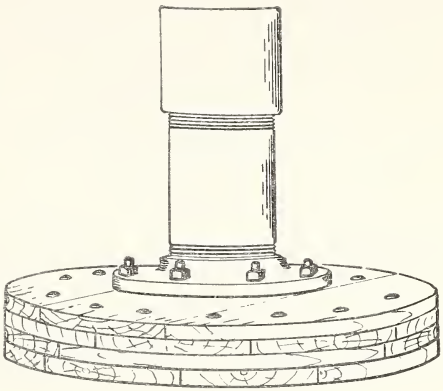

FIGURE 40.—Wooden surge block used in developing wells. A length of pipe is attached to the coupling to give additional weight.

DEVELOPING WITH AIR

Irrigation wells are sometimes developed by means of compressed air. This method is best suited to wells of relatively small diameter in which there is considerable depth of water in proportion to the total depth of the well. Compressed air is used either to pump the water from the well or to surge the water in the well (fig. 41). Either method requires an air compressor of ample capacity capable of developing a pressure of from 100 to 150 pounds per square inch and a motor or engine with sufficient power to operate the compressor. The power available should not be less than that necessary to pump the well at its maximum capacity.

The use of compressed air, as a means of pumping a well to develop it, is limited to wells in which the depth of water exceeds two-thirds of the total depth of the well. When this method is used, an eduction pipe for discharging the water is lowered into the well to within 2 feet of the bottom. Sometimes the eduction pipe is dispensed with, the well casing being used to discharge the water,

but this practice is not recommended because of the inefficient use of air under these circumstances. For irrigation wells of ordinary size, that is, having a capacity of not to exceed 1,000 gallons per minute, a 6- or 8-inch eduction pipe and a 2-inch air line should be used. The well is pumped by turning air into the air line, and the rate of pumping is varied by changing the rate at which the air is turned into the line. Pumping should be intermittent in order to permit the water to build up in the well to the static level from time to time. The pressure tank on the compressor should be pumped up to capacity while the water is rising in the well, and this large volume of air should be released suddenly in the bottom of the well through the air line thereby causing the water in the well to rush upward through the eduction pipe and the space between the eduction pipe and the casing. The inertia of the column of water causes it to resist the sudden movement, and as a result water is forced out through the perforations and into the water-bearing formation. The reversed flow loosens more fine material, and when pumping is resumed this material is washed out. In order to obtain the best results when turning the large volume of air into the well, the air line should be lowered until it extends below the eduction pipe. When sand is no longer brought in at the original position the equipment should be raised and the process repeated.

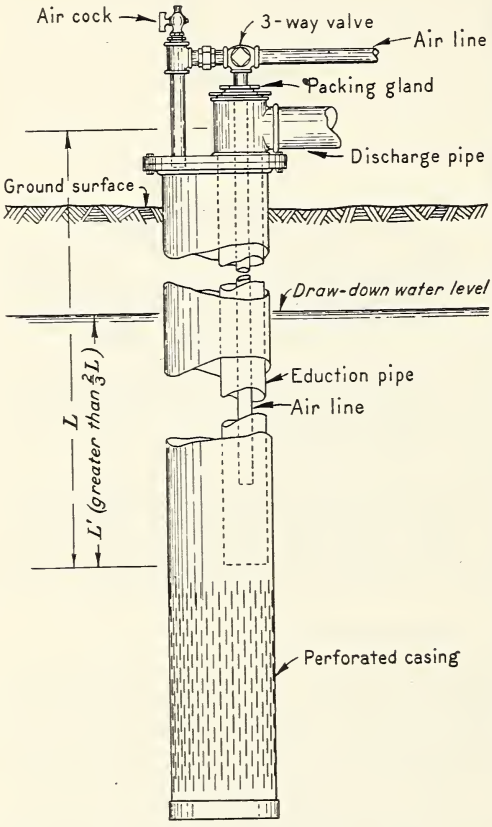

FIGURE 41.—Air-lift-pump installation for developing well by pumping and backwashing.

Developing wells with an air-lift pump is very effective where a large quantity of sand is being brought in. There are no moving parts in the pump to be injured by the sand. If this process does not develop the well sufficiently, the eduction pipe and air line should be removed, and the well should be surged with a mud scow or surge block as previously explained. After the well has been thoroughly surged the air equipment should be reinstalled, and development continued by pumping until no more sand appears in the water.

BACKWASHING

Another method of developing wells by means of air is known as backwashing. When this method is used, the water in the well is forced out through the perforations by means of the pressure of the air on the water, but it cannot be used unless the water in the well stands at a considerable height above the perforated portion of the casing. When this method is used, the top of the casing is sealed with an airtight cap through which the air line extends (fig. 41). The air line is equipped with a three-way valve so that the pressure in the well can be released at any time. When air is turned into the air line, the water in the well is forced out through the strainer until the air begins to escape through the perforations. The air is then shut off, and the pressure in the well released by opening the three-way valve because there is danger of air logging the water-bearing formation if it is allowed to escape through the perforations.

A pressure gage on the air line is very desirable in order to know definitely when the pressure has built up high enough to force air through the perforations in the strainer. As soon as the air starts to escape, the pressure on the gage will no longer rise. When the pressure is released, the water will flow back into the well through the perforations and bring in fine sand from the area surrounding the strainer. This process is repeated until no more sand is brought in. The cap is then removed, and the accumulated sand bailed out. A large volume of air is lost each time the pressure is released, but it can be eliminated to a large extent by putting an airtight plug in the well at the water surface rather than by capping the casing at the ground surface.

A combination of the backwashing and pumping method of developing wells by means of air is more effective than either of the methods used separately. When the combination method is used, the eduction pipe is run through the airtight cap on the well. The air line is inserted in the eduction pipe as before, and a separate air line with an air cock is run through the cap (fig. 41). The eduction pipe is carried down into the well to a point a foot or two above the top of the perforated portion of the casing so that it will not be possible to air-log the strata. The same effect could be obtained by installing a pressure gage and shutting off the air when the gage indicated that the water had been forced down to the top of the perforated section.

To develop the well the air cock is opened and air is turned into the airline in the eduction pipe. This pumps water out of the well and washes some of the fine material out of the water-bearing formation. The well is pumped in this manner until the water clears; the air is then shut off and the water allowed to return to its original level. As soon as this occurs the air cock is closed and air turned into the other line, thereby building up the pressure in the well and forcing out the water through the perforations until the water drops to the level of the bottom of the eduction pipe. When the air begins to escape through this pipe, the three-way valve is closed and the air cock opened. The water then flows rapidly into the well through the per-

forations. This process is repeated several times, after which the air is turned into the eduction pipe again, and the well pumped until the water clears. The process of alternately pumping and backwashing is continued until no more sand comes into the well. Most of the sand that is washed into the well is carried out by the pump, but when the development is completed the well should be sounded, and, if any sand remains there, it should be pumped out by lowering the eduction pipe to the top of the sand. When the developing process is completed, the well should be pumped at the maximum rate for several days to open up the pores in the area outside the influence of pumping or backwashing with air. Developing wells by this process is a rapid and effective way to accomplish the desired results. In combination with the surging method, it is capable of developing a well to its full capacity.

DEVELOPING WITH SOLID CARBON DIOXIDE

Developing with solid carbon dioxide has been tried with considerable success under some conditions but in general the cost is too great. The process used is similar to the backwashing method (p. 69) except that the pressure is built up by the evaporation of the solid carbon dioxide.

TESTING WELLS

After the well has been developed and pumped at the maximum rate possible long enough to establish equilibrium between the discharge and the draw-down, it should be thoroughly tested to determine its characteristics. The choice of the type of pump, the determination of the economical yield of the well, and the horsepower required to operate the plant will depend to a large extent on the results of the test. In the past, many farmers purchased pumping plants without having had their wells tested, and as a result some of the plants were later found to be unsatisfactory because the capacity of the well was not sufficient to supply the pump or the draw-down was so great that pumping was uneconomical. Many of these plants had to be replaced at a considerable financial loss to the farmer. In view of these facts, every well should be tested even though the characteristics of nearby wells are definitely known, because wells only a few hundred yards apart often differ widely in yield.

The information to be obtained from a well test is the location of the static water level and the yield and depth to water when the well is being pumped at different rates. From these data the draw-down, the yield, and the specific capacity, that is, the yield per foot of draw-down, can be computed. When testing deep wells in which the water-bearing formations are of great thickness or in which the water in the formations is under pressure, it is not necessary to pump the well at its maximum rate to determine its characteristics, because the yield is almost directly proportional to the draw-down. That is, if a draw-down of 5 feet yields 500 gallons per minute, one of 10 feet will yield approximately 1,000 gallons per minute. This statement is not true, in general, for shallow wells, and for this reason the test

of these wells should preferably be carried on until the maximum capacity of the well is reached. If the well was developed by pumping, the equipment used for developing the well can be used for making the well tests, and, if other methods were used to develop the well, a pump will have to be installed to make the tests.

Before starting the test on a well it is necessary to measure the depth to the static water level. After this the well is pumped at the maximum rate possible for a sufficient time for the draw-down and the discharge to become constant. When a condition of equilibrium is reached, the discharge of the pump is measured and the depth to water noted. The difference between this depth and the depth to the static water is the draw-down. The pumping rate is then reduced until the draw-down is about one-fifth less than it was before. Pumping is continued at this rate until the draw-down becomes constant when the discharge and draw-down are measured again. The discharge is then reduced until the draw-down is two-fifths less than the maximum. This process is repeated until the elevation of the surface of the water in the well returns to its original value.

From these data a curve is plotted showing the relation between the draw-down and the discharge. Figure 4 shows a typical discharge-draw-down curve for a deep well in an artesian formation and for a shallow well not flowing under pressure. The curve for the deep well is a straight line, whereas that for the shallow well bends upward. This means that the discharge per foot of draw-down from the deep well is constant, and that from the shallow well is constantly decreasing. It is evident therefore that the higher the rate at which the shallow well is pumped the smaller will be the discharge per foot of draw-down. That is why it is uneconomical to pump a well of this type at its maximum capacity. Under ordinary conditions it will be found most economical to pump shallow wells at a rate that does not make the draw-down exceed one-half the depth of the water in the well. Deep wells usually are not drawn down to the same extent as shallow wells, but the limitation is not the reduction in discharge per foot of draw-down; it is the increase in the lift which restricts the depth to which the well should be pumped.

The measurement of the discharge, when testing the well, should be made carefully. Either a weir, Parshall measuring flume, orifice plate, or other suitable device may be used. The methods of making these measurements are described in bulletins by Parshall (*28*) and by Christiansen (*2*). Orifice plates that screw on the end of the discharge pipe of the pump provide one of the simplest means of measuring the discharge from a well. However, unless standard plates are used for which discharge tables have been prepared, they should be calibrated by comparison with some standard measuring device.

Where the discharge from the pump is into a pipe line, the devices previously mentioned cannot be used. Under these circumstances the discharge measurement can be made by installing a thin orifice plate in the line or by timing the flow of color or salt through a known length of the pipe. The thin orifice plate differs from the orifice plate on the end of the discharge pipe in that it is a sub-

merged-flow orifice and requires the measurement of two heads to determine the discharge. It is important that these heads be measured at the same points that were used when the orifice was calibrated. When the color or salt-velocity method is used to measure the discharge, the inside diameter of the pipe, as well as the length and the time of transit of the salt or color must be accurately determined. If there is any deposit or encrustation in the pipe, this method should not be used as it is impossible to determine the area of the pipe accurately. The reach of the pipe used for measuring the velocity should not be less than 100 feet in length. Whichever method of measuring the yield from the well is used, it is desirable to make several determinations of each discharge in order to eliminate errors and minimize the effect of minor fluctuations in the flow.

The depth to water in shallow wells can be measured accurately without difficulty, but special equipment must generally be used to determine the location of the water surface in deep wells. A tape and weighted float is all that is necessary to measure the depth to water in a shallow well. The tape is lowered until the float strikes the water. The reading of the tape at the ground surface, corrected for the distance from the end of the tape to the water line on the float, is the desired depth. This method cannot be used on deep wells because the length of tape required is so heavy that it is difficult to determine when the float hits the water, and usually there is not enough clearance between the pump bowls and the casing to let the float pass. Some deep-well pumps are equipped with pressure gages (fig. 39) and air lines of known lengths. The pressure in feet of water required to force all the water out of the air line subtracted from the length of the air line gives the depth to water. If the gage is calibrated in pounds, the gage reading can be converted into pressure in feet of water by multiplying the reading in pounds per square inch by 2.31. If the gage is calibrated in inches of mercury, the conversion can be made by multiplying by 1.13. The air line should extend about 10 feet below the limit of the draw-down, but it should not end within 5 feet of the suction inlet of the pump because of the disturbed flow near this point.

Another method of measuring the depth to water in deep wells is to use an electric sounder. There are several types of this device, but the essential feature of all of them is the electric contact made when the sounder strikes the water surface. One of the simplest and best of these devices consists of an insulated wire weighted at the lower end by a flexible lead sheath. The lower end of the wire is bare, but it is shielded from spray or from contact with the casing or the pump column by an insulated sleeve. The other end of the wire is attached to a telephone bell ringer or to a telephone head set and battery. A lead is run from one of the terminals of the battery or bell ringer to the pump column or to the casing. Then when the bare end of the wire strikes the water surface, the circuit will be completed, and it will be possible to hear when the contact is made by the ringing of the bell when turning the crank or by the click in the head set. The depth to water is determined by measuring the length of cable in the well. A two-wire cable with a small electric-

light bulb in the circuit operated by a storage battery may also be used. This sounder contains a small float that rises and breaks the electric circuit when it sinks into the water. The light burns until the circuit is broken by the sounder sinking into the water. This device has the advantage that it is possible to tell instantly whether the circuit is in order by noting whether the light is burning.

COST OF CONSTRUCTING WELLS IN 12 WESTERN STATES

The cost of constructing wells varies with the size and depth of the well, the method of drilling, the nature of the material encountered, the locality, the kind of casing used, the method of perforating the casing, and the time spent in developing and testing the well. It is possible to estimate the cost of these various items, but the values given should be used merely as guides for making a preliminary estimate of the cost of a well, the actual cost will be determined by the contract made with the well driller for the particular well and the cost of casing at the time the well is being drilled. The following data on the cost of well drilling and of well casing are based on prices prevailing in 1938 and cover only the States in the arid sections of the West.

CALIFORNIA

In California most wells are drilled by the California or mud-scow method and are cased with double stovepipe casing. The hydraulic-rotary method is used in some sections and in that case the stovepipe casing is built up into sections 20 to 30 feet long and installed after the well is drilled. The materials encountered in California wells vary from fine sand to hard rock and the drilling price varies accordingly. The range of prices for drilling wells by the mud-scow method and the price of stovepipe casing and well rings in California are given in table 3. The lowest prices are for drilling in sandy formations where no difficulty is experienced in putting down wells and the highest prices are for drilling where beds of boulders are encountered or where the well is largely in hard rock. The prices for drilling are for a minimum depth of hole, ordinarily 100 feet. If the well is shallower than this a charge which should not exceed $50 is usually made for moving the rig to the site of the well. There is frequently a maximum limit also to the depth to which the driller will go for the quoted price. This limit varies from 150 to 500 feet. If the well exceeds the maximum depth there is frequently an additional charge per foot which increases as the depth increases. The prices given include the cost of installing and perforating the casing but do not include the cost of casing nor of developing and testing the well. The cost of developing and testing varies between $20 and $50 per day depending on the size of the equipment required. If the well is gravel-packed the price does not include the gravel.

TABLE 3.—*Range of prices for drilling wells in California by the California or mud-scow method and of casing and well rings at the factory*[1] *in 1938*

Diameter[2] (inches)	Cost of drilling per foot	Cost of double well casing per foot				Well rings[3]	
		16-gage	14-gage	12-gage	10-gage	Size	Cost
	Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Inches*	*Dollars*
6	1.00 to 3.75	0.98	1.17	1.22	1.55	6× ¾	10.00
8	1.00 to 4.00	1.18	1.43	1.50	1.89	8× ¾	17.50
10	1.00 to 4.25	1.41	1.69	1.88	2.34	8× ¾	19.00
12	1.25 to 4.50	1.64	1.98	2.18	2.75	8×1	30.00
14	1.50 to 4.75	1.89	2.26	2.48	3.17	10×1	34.00
16	1.75 to 5.00	2.14	2.56	2.81	3.56	10×1	39.00
18	2.00 to 5.25	2.38	2.85	3.15	3.99	10×1¼	59.00
20	2.25 to 5.50	2.64	3.18	3.50	4.40	10×1¼	73.00
22	2.50 to 5.75	2.92	3.49	3.82	4.82	12×1	83.00
24	2.75 to 6.00	3.16	3.79	4.19	5.17	12×1	90.00

[1] Factories are located in all large towns in the area irrigated by pumping.
[2] Sizes refer to inside diameters.
[3] The quotations and dimensions are for rings of average size; heavier or lighter rings would be correspondingly higher or lower in price.

The quotations on casing are factory prices. In order to obtain the price delivered at the well the freight from the nearest factory to the site should be added. Casing carries a high freight rate because of its bulk and for this reason it is important that the rates be investigated. Stovepipe casing assembled in lengths from 6 to 21 feet long costs about 10 percent more than plain casing and two-ply starter sections cost about 25 percent more than plain casing. Three-ply starters cost about twice as much as plain casing. Casing perforated at the factory costs 8 cents per foot additional for each inch of diameter for 10-gage casing, 4 cents additional for 12-gage, and 2 cents additional for 14- and 16-gage. The quotations on well rings in table 3 are for welded rings of average weight. Forged rings cost more.

OREGON

Irrigation wells in Oregon are mostly of the open-pit type, but there are also some drilled wells. The pit wells are from 5 to 8 feet square and are from 10 to 20 feet deep. These wells have wooden casing consisting of 2-inch lagging supported by wooden frames. The cost of digging these wells is about $1 per foot for each foot in width and the cost of the curb is from $2 to $4 per foot of depth depending on the size. Drilled wells in Oregon are, as a rule, put down with percussion tools and are cased with standard casing. The depths range from 50 to 400 feet, but most wells are less than 150 feet deep. The average cost of drilling wells of this type is as follows: 6-inch, $1.75; 8-inch, $3.25; 10-inch, $4.75; 12-inch, $6.75; 14-inch, $9; and 16-inch, $11.50. The prices are for drilling only. The cost of standard well casing is given in table 4. The prices for drilling are for ordinary conditions, for drilling rock or in boulders, the prices are about 50 percent higher.

TABLE 4.—*Approximate cost per foot of standard black well casing with couplings in less than carload lots in 1938 and pertinent data on weights and dimensions*

Size (inches)[1]	Price per foot[2]	Weight per foot[3]	Diameter			Thickness	Threads per inch
			Outside casing	Inside casing	Outside couplings		
	Dollars	*Pounds*	*Inches*	*Inches*	*Inches*	*Inch*	*Number*
5⅝	0.89	10.50	6.00	5.672	6.664	0.164	14
6⅝	1.14	13.00	7.00	6.652	7.692	.174	14
7⅝	1.25	16.00	8.00	7.628	8.788	.186	11½
8⅝	1.60	19.00	9.00	8.608	9.788	.196	11½
9⅝	1.92	22.75	10.00	9.582	10.911	.209	11½
10⅝	2.25	26.75	11.00	10.552	11.911	.224	11½
11⅝	2.65	31.50	12.00	11.514	12.911	.243	11½
12½	3.07	36.50	13.00	12.482	14.025	.259	11½
13½	3.78	42.00	14.00	13.448	15.139	.276	11½
14½	4.52	47.50	15.00	14.418	16.263	.291	11½
15½	5.00	52.50	16.00	15.396	17.263	.302	11½

[1] Inside diameter. Also frequently designated according to outside diameter as o. d. pipe.
[2] These prices apply to all the major cities in the West, except on the Pacific coast where prices are somewhat lower. To obtain local price add freight from nearest warehouse to local freight station.
[3] Weight includes couplings.

WASHINGTON

Hand-excavated pit-type irrigation wells are used also in some sections of Washington. Some of these wells are 150 feet deep. The pits are usually 5 or 6 feet square and above the water table they are curbed with 3-inch planks set horizontally. Metal casing, 5 feet in diameter perforated with round holes is sunk into the water-bearing formation. The cost of a well of this type including the wood curb and the metal casing is about $20 per foot. There are also many drilled wells used to supply water for irrigation. These wells are mostly of small diameter and are cased with standard well casing. The average cost of drilling these wells is about the same as given for Oregon. The cost of developing, perforating, and testing is $3.50 per hour.

IDAHO

Most irrigation wells in Idaho are drilled with standard tools. The wells range in diameter from 8 to 36 inches and in depth from 30 to 150 feet. Nearly all wells are cased, but in some lava-rock formations no casing is necessary. Standard screw casing is used in the 8- and 10-inch wells, welded casing three-sixteenths to one-fourth of an inch thick is used in the 12- to 30-inch wells, and one-fourth of an inch thick is used in the 36-inch wells. Some of the casing is perforated before installing and some is perforated in place. About half of the wells are gravel-treated. The average cost of drilling wells is from $1 to $2 per foot for wells from 4 to 6 inches in diameter; from $1.50 to $2.50 for 8-inch wells; from $2.50 to $3 for 10-inch wells; and from $3 to $5 for 12-inch wells. The average cost of drilling the larger wells is $6 per foot for the 14-inch size; $7.50 for the 18-inch size; $9 for the 24-inch size; $10.50 for the 30-inch size;

and $12 for the 36-inch size. The cost of the standard well casing is given in table 4. The price for drilling includes the installation of the casing but does not include developing and testing. The prices are for wells not over 400 feet deep in ordinary valley fill. For additional depth between 400 and 600 feet the cost of drilling is about 25 percent higher. For drilling hard lava the price per foot is double the standard rate. The cost of perforating the casing averages about $50 and the cost of development about $100. If a gravel envelope is used, the gravel will cost from $2.50 to $4 per cubic yard and from 10 to 100 cubic yards may be required. The approximate cost of welded casing at Boise is $3.50 per foot for ¼-inch casing 18 inches in diameter, $4.30 per foot for ¼-inch casing 24 inches in diameter, and $6.50 per foot for ¼-inch casing 36 inches in diameter.

NEVADA

Irrigation by pumping from wells is not practiced extensively in Nevada, but there are some irrigation wells in the Truckee-Carson district and in the southern part of the State. In the Truckee-Carson district gravel-packed wells are being put down at the present time. These wells are 10 inches or more in diameter and are seldom more than 250 feet deep. They are cased with stovepipe casing which may be either perforated in place or before inserting. The hydraulic-rotary method is used in drilling these wells. The wells in the southern part of the State are frequently under artesian pressure and range in depth from 300 to 1,000 feet and are 8 inches or less in diameter. They are drilled with standard tools or with a combination of standard tools and hydraulic equipment. Screw casing is used and it is perforated in place opposite the water-bearing strata with a knife perforator. The cost of drilling the gravel-packed wells, including the cost of casing, varies between $5 and $10 per foot depending on the size of the well and the conditions encountered. The wells in the artesian area are much cheaper to construct, the range of prices being from $1.50 to $2 per foot. The price does not include the cost of the casing which may be approximated from the prices given in table 4.

UTAH

The most common type of irrigation well in Utah is a hand-excavated pit well having either a brick or a concrete curb. These wells are from 4 to 8 feet in diameter and from 35 to 100 feet in depth. A 10- or 12-inch perforated casing is sunk in the bottom of some of these pits for the purpose of increasing the yield from the well. The cost of digging these pits cannot be determined very definitely because most of them are dug by the farmers themselves, but it is estimated that the total cost including the curb is about $2.50 per foot of diameter. Some irrigation wells in Utah are drilled with standard tools. The prevailing price per foot for drilling is as follows: $1 for 4-inch wells, $1.25 to $2 for 6-inch wells, $2 to $3 for 8-inch wells, and $3 to $4 for 10- and 12-inch wells. In hard rock or boulders prices are higher but in silt formations the price may be as low as $0.60 per foot for 4-inch wells and $2.75 per foot for 12-inch wells.

ARIZONA

Irrigation by pumping has been practiced successfully in Arizona for many years. The original wells were of the shallow-pit type and were excavated by hand, but at present most of the wells are being put down by the California or stovepipe method although standard tools are frequently used in combination with the California mud-scow equipment. The diameters are between 16 and 30 inches, but most wells are between 16 and 20 inches in diameter and from 150 to 350 feet deep. Double stovepipe casing which is perforated in place opposite the water-bearing formations is used in the wells. They are not gravel-packed. The cost of drilling, and the price of casing and well rings or drive shoes at Phoenix are given in table 5. The prices given include perforating but do not include developing or testing. Developing with a mud scow costs $3 per hour and 2 or 3 days are usually required to do the work properly.

TABLE 5.—*Average cost of drilling wells by the California or mud-scow method in Arizona and of stovepipe casing and well rings at Phoenix, in 1938*

Diameter [1] (inches)	Cost of drilling per foot [2]	Cost of double well casing per foot				Well rings [3]	
		16-gage	14-gage	12-gage	10-gage	Size	Cost
	Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Inches*	*Dollars*
6	0.75 to 1.00	0.91	1.08	1.11	1.42	6× ¾	10.00
8	1.25 to 1.50	1.10	1.33	1.37	1.73	8× ¾	17.50
10	1.50 to 1.75	1.31	1.57	1.72	2.14	8× ¾	19.00
12	2.00 to 2.50	1.52	1.84	1.99	2.52	8×1	30.00
14	2.75	1.75	2.10	2.28	2.90	10×1	34.00
16	3.00	1.98	2.38	2.58	3.26	10×1	39.00
18	3.50	2.22	2.64	2.89	3.65	10×1¼	59.00
20	3.00 to 3.50	2.46	2.95	3.20	4.03	10×1¼	73.00
22	4.00	2.71	3.24	3.50	4.41	12×1	83.00
24	4.00	2.93	3.52	3.84	4.74	12×1	90.00

[1] Sizes refer to inside diameters.
[2] Prices are for drilling wells under average conditions. The cost of perforating is included, but the cost of developing is not.
[3] The quotations and dimensions are for rings of average size; heavier or lighter rings would be correspondingly higher or lower in price.

NEW MEXICO

Although only a small area of New Mexico is irrigated by pumping from wells, there is at present considerable interest in providing water for irrigation by this method. In the shallow-water sections irrigation wells are in most cases drilled with rotary equipment, although standard cable tools are sometimes used. The 20- and 30-inch wells are most common. Twelve-inch casing is used in the 20-inch wells and 15-inch in the 30-inch. The space between the casing and the wall of the well is filled with gravel. The price for drilling is $3 per foot for the 20-inch wells and $5 per foot for the 30-inch wells. If the depth of the well is less than 100 feet the prices are about 50 percent higher. These prices include placing the gravel packing and perforating the casing but do not include the gravel for the envelope or the gas for the torch which is used in cutting the perforations. When standard tools are used the price is $2 per foot for 12-inch wells and $2.50 per foot for 15-inch wells. The price for drilling deep wells, such as artesian wells, is $2.50 for 10-inch holes and $3 for 12-inch holes. This price includes setting the casing and

cementing it into the cap rock but does not include the cement. The approximate prices for well casing and standard pipe are given in tables 4 and 6.

TABLE 6.—*Approximate cost per foot of standard black pipe with couplings in less than carload lots in 1938, and pertinent data on weights and dimensions*

Size (inches) [1]	Price per foot [2]	Weight per foot [3]	Diameter			Thickness	Threads per inch
			Outside pipe	Inside pipe	Outside coupling		
	Dollars	*Pounds*	*Inches*	*Inches*	*Inches*	*Inch*	*Number*
4	0.68	10.889	4.500	4.026	5.091	0.237	8
5	.92	14.810	5.563	5.047	6.296	.258	8
6	1.19	19.185	6.625	6.065	7.358	.280	8
7	1.57	23.769	7.625	7.023	8.358	.301	8
8	1.65	25.000	8.625	8.071	9.358	.277	8
9	2.45	34.188	9.625	8.941	10.358	.342	8
10	2.13	32.000	10.750	10.192	11.721	.279	8
11	3.35	46.247	11.750	11.000	12.721	.375	8
12	3.05	45.000	12.750	12.090	12.958	.330	8

[1] Nominal inside diameter.
[2] These prices apply to all the major cities in the West except on the Pacific coast where prices are somewhat lower. To obtain local price add freight from nearest warehouse.
[3] Weight includes couplings.

COLORADO, KANSAS, AND NEBRASKA

In Colorado, Kansas, and Nebraska most of the wells are in gravel formations and are relatively shallow, very few being over 100 feet deep. These wells are generally from 12 to 48 inches in diameter and are drilled by means of bailers or orange-peel buckets. Sometimes an earth auger is used to start the wells and to drill through beds of clay. Standard tools are used when beds of boulders or layers of rock are encountered. Some of the deeper wells in Kansas are drilled by the hydraulic-rotary process. The wells in Colorado, Kansas, and Nebraska are cased almost exclusively with galvanized-iron casing which is made both plain and perforated. There are several types of perforations used, but the chisel-type slot is the most common. Most of these wells are gravel-packed. Large wells from 6 to 10 feet in diameter are occasionally found. These wells are generally excavated by hand, but some of them are put down by special methods such as described on page 51. These large wells are rarely more than 30 feet deep, but there is one 8-foot well in Nebraska that is 70 feet deep. Wood, brick, or concrete casing is used in these large wells.

The approximate cost of drilling wells from 6 to 48 inches in diameter in Colorado and the price of galvanized-iron casing at Denver are given in table 7 (*5*). The drilling costs do not include the cost of developing or testing but do include the installation of the casing. Similar prices prevail in Kansas and Nebraska. The quotations on casing are for ordinary galvanized iron, the prices for rust-resistant steel casing being higher. The cost of excavating and casing large wells in Colorado is about $2 per foot of diameter. Pumping the water from the well while it is being dug is not included. Large wells excavated by the special process previously referred to cost $2.50 per foot of diameter, including the cost of the casing. This process is used principally in Nebraska. On account of the many

uncertainties in connection with drilling wells by the hydraulic-rotary method which is used in Kansas, drilling is usually contracted on a day basis.

TABLE 7.—*Approximate cost of drilling wells in Colorado by the sand-pump or orange-peel-bucket method and of plain and perforated galvanized-steel well casing at Denver, Colo., in 1938 (5)*

[Iron bands required at each joint and at top and bottom for values below heavy line. The approximate cost of these bands per pound, welded and drilled, is 25 cents for 1-inch bands, 17 for 1½-inch, 12½ for 3-inch, and 10½ cents for bands wider than 3 inches]

Size (inches)	Drilling cost per foot	Cost of casing per foot							
		16 gage		14 gage		12 gage		10 gage	
		Plain	Perforated	Plain	Perforated	Plain	Perforated	Plain	Perforated
	Dollars	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*	*Dollars*
6[1]	1.00	0.55	0.68	0.69	0.77				
12	2.50	.99	1.22	1.22	1.51	1.65	2.14	2.17	2.72
14	3.25	1.12	1.42	1.42	1.77	1.95	2.45	2.46	3.10
16	3.75	1.29	1.59	1.60	2.02	2.20	2.76	2.79	3.48
18	4.50	1.45	1.81	1.79	2.25	2.45	3.09	3.12	3.90
24	6.50	1.95	2.41	2.42	2.99	3.25	4.08	4.11	5.11
30	7.50	2.44	3.05	3.06	3.78	4.10	5.10	5.18	6.45
36	8.50	2.93	3.64	3.64	4.55	4.98	6.19	6.26	7.79
48	10.00	3.90	4.87	4.87	6.06	6.58	8.21	8.60	10.72

[1] Test hole. For more than 1, a reduction in price is usually made.

TEXAS

Less than 1 percent of the land area of Texas is irrigated and of this area only about 10 percent is irrigated from wells. The water in many of the irrigation wells is under artesian pressure. Some wells flowed originally but the heavy draft on the water-bearing formations caused by irrigation has reduced the pressure in most areas until all the wells have to be pumped. The irrigation wells range between 100 and 2,000 feet in depth. Nearly all are of small diameter, the range being from 4 to 14 inches. The wells are put down by means of hydraulic-rotary drills and standard tools, but the hydraulic-rotary method is used most often. Nearly all of the wells are cased throughout the entire depth with standard well casing. Some, however, which are bored in rock, are cased only partly. Special strainers are used where the water-bearing formations are very fine. The cost of drilling varies between $1 and $2.50 per foot depending on the diameter of the well, and the depth and character of the material encountered. The price of well casing and standard pipe is given in tables 4 and 6.

SUMMARY

The principal items that should be given consideration before beginning the construction of a pumping plant for supplying water for irrigation are the legal status of pumping for irrigation, the quantity of water required for the crops to be irrigated, the quality and quantity of water available from the underground source, the

economic limit of pumping lift and the cost of pumping, the well contract, the preparation of the land for irrigation, the suitability of the climate and the soil for growing crops under irrigation, the accessibility of markets, and the facilities for financing the undertaking.

The source of supply for irrigation wells is the water that is stored in the soil in saturated strata of sand and gravel. The quantity of water that can be drawn from this underground source depends on the thickness and extent of the water-bearing formation, the character of the material in the formation, and the rate at which the supply of water in the formation is being replenished.

The rate at which ground water moves in a water-bearing formation depends on the slope of the water table, the size, shape, uniformity, and compactness of the particles of sand and gravel, and on the temperature of the water. The formulas that have been developed for determining the rate of flow have not proved satisfactory because of the difficulty in evaluating the effect of the different factors. The most satisfactory results are obtained when the rates of flow are determined by direct measurements.

The capacity of an irrigation well depends on the radius of the well and of the circle of influence, the type of strainer, the draw-down, and the depth and character of the water-bearing formation. The theoretical relation of these factors to the discharge has been determined and expressed by formulas, but the observed capacities of wells have not agreed very closely with those determined from the theoretical formulas. This condition is probably caused by the fact that the factors involved cannot be determined accurately.

Although these formulas do not give satisfactory results when used to compute the discharge from the well, they can be used to determine the relative effect of the various factors that influence the discharge. The formulas show that increasing the diameter of a well does not increase the discharge in the same proportion, that if the draw-down is not too great, the discharge is proportional to the draw-down and to the thickness of the water-bearing formation, and that the discharge is proportional to the transmission constant.

Batteries of wells should be used where the required quantity of water cannot be obtained from a single well.

The mutual interference of wells in a battery reduces the capacity of each well, but the interference is not important if the wells are spaced from 50 to 75 feet apart. Deep wells should be spaced at greater intervals because of their greater cost.

Test holes should be put down for the purpose of deciding whether conditions are favorable for digging an irrigation well. The soil auger and the standard drilling methods, except possibly the California method, are all used in drilling test wells. The auger, sand-bucket, standard-tool, and hydraulic-rotary methods are used in the same manner as when drilling irrigation wells, the principal difference being that a smaller hole is put down. Each of these methods, except the hydraulic-rotary process, will supply the material for an accurate well log.

The jetting process is not used for drilling irrigation wells, but it is one of the fastest methods of drilling test holes in unconsolidated material and is especially effective in clay. The information ob-

tained by the jetting process is not very reliable because the materials from the different formations are mixed together as they are carried to the surface by the stream of water used in the process.

The self-cleaning or hollow-rod method can be used in harder materials than the jetting process, and it also supplies more accurate information about each formation because the materials from different strata are not mixed together while they are carried to the surface by the flow of the water in the drill stem.

Wells used for irrigation purposes are classified according to their method of construction as dug wells, bored wells, large pits, and drilled wells.

Dug wells are open pits, usually circular, usually from 6 to 10 feet in diameter which are excavated by hand and cased with wood, brick, stone, concrete, or metal curbs that frequently also act as strainers. The yield of these wells depends largely on the depth they penetrate into the water-bearing formation, the better wells producing from 500 to 1,500 gallons per minute. The most satisfactory results are generally obtained if the well is excavated to water by hand and then finished by sinking perforated casing with a bailer or orange-peel bucket. Farmers frequently attempt to put down this type of well themselves but often without success because they have difficulty in getting the casing down deep enough into the water-bearing formation.

Large open pits excavated with teams and scrapers or a dragline are also used as irrigation wells. This type of well is often unsatisfactory because the limit of draw-down is usually so small that not enough water is drawn into the well to supply the desired quantity. Pits yielding 1,000 gallons per minute are rare.

Shallow wells in clay formations underlain with gravel are frequently bored down to the water-bearing formation with an earth auger. The perforated casing is then sunk into the gravel by means of a sand bucket or bailer. The yield of wells put down in this manner varies from 500 to 1,500 gallons per minute depending on the water-bearing medium.

Wells sunk by means of percussion drills, rotating drills, water jets, or combinations of these tools are known as drilled wells. The methods used in sinking wells by means of these tools are known as the standard method, the California or stovepipe method, the hydraulic-rotary method, the sand-bucket and orange-peel-bucket method, the jetting method, and the hollow-rod or self-cleaning method.

The standard method of sinking wells is used principally in drilling in hard rock or boulders. The material in the hole is broken up by the percussion of a heavy drill which is raised and lowered at regular intervals by the drill rig. The drillings are removed from the hole by means of a sand bucket or bailer. Holes can be drilled to great depths by this method. The diameters of the wells range from 6 to 24 inches, but smaller holes are sometimes put down for test purposes. Both standard well casing and double stovepipe casing are used in these wells, and the casing is usually perforated in place. When the water-bearing formation is suitable, very good wells are obtained by this method. The capacities range from several hundred to several thousand gallons per minute.

The California or stovepipe method is similar to the standard method except that the solid tools and the bailer are replaced by the mud-scow which serves both purposes. The method is best suited for drilling fairly deep wells in unconsolidated material. The diameters of the wells put down with mud scows range from 4 to 30 inches, but usually are 16 to 20 inches. Most wells of this type are from 500 to 1,000 feet deep, but some of them are considerably deeper. These wells are cased with double stovepipe casing which is forced down by means of hydraulic jacks. The casing is usually perforated in place, but some factory-perforated casing is used, particularly in shallower wells. The yield from these wells varies through wide limits. In good formations wells producing 4,000 or 5,000 gallons per minute are sometimes obtained, but many wells do not produce more than 500 gallons per minute.

The sand-pump or the orange-peel-bucket method of drilling wells is frequently used when the water-bearing formations are at shallow depths in unconsolidated material free from layers of rock or beds of boulders. These wells are usually from 12 to 48 inches in diameter and are rarely more than 100 feet deep. The material is removed from the well by means of a sand pump or orange-peel bucket which is operated by a portable well rig or a simple hoist. These wells are, as a rule, cased with lightweight riveted metal casing which is perforated before being placed in the well and is forced down by levers or weights. Concrete casing, in the form of precast rings or a monolithic shell, is sometimes used. These wells ordinarily yield from 500 to 1,000 gallons per minute although occasional wells have higher yields. If the yield falls below 500 gallons per minute, two or more wells are usually put down.

The hydraulic-rotary process, which utilizes a rotating bit for loosening the material in the well and a stream of water heavily charged with clay for washing out the drillings and strengthening the walls of the hole, is adapted to drilling irrigation wells in unconsolidated material. This process is particularly effective in drilling through layers of clay which frequently retard the progress when other methods are used. Wells up to 18 inches in diameter and several hundred feet deep are easily put down by this method, and, if a reamer is used, a still larger hole can be drilled successfully. The wells drilled by the hydraulic-rotary method are cased with double stovepipe casing that has been built up in sections or with well casing. Perforating is usually done before the casing is installed. The yield from these wells is similar to that from wells put down by the California method. It is sometimes claimed that the yield from the water-bearing formations is permanently reduced by the deposit of clay from the jetting water when this method is used. The truth of this statement cannot be definitely established, but it is known that this is one of the fastest and cheapest methods for putting down irrigation wells.

Gravel envelopes or gravel screens are used on wells in fine sand and silty gravel to reduce the resistance to the flow of the water toward the well and to fill the cavities caused by the sand washing into the well. Fairly coarse gravel of a uniform size is used for the screens. If the water-bearing formation is coarse, it is doubtful whether the yield of the well will be increased by a gravel screen.

After an irrigation well is completed it should be developed by washing out the fine particles in the water-bearing medium around the strainer. The washing is accomplished by pumping the well at different rates, by agitating the water with a surge block or by a mud scow, by surging or pumping with air or solid carbon dioxide, or by a combination of these processes. Sometimes, a jet of water is used.

Every well should be tested to determine its capacity and to provide the information necessary for choosing the proper size of pump and motor for the plant. The test should consist of the measurement of the discharge and the draw-down when pumping at several different rates. Pumping should continue at each rate until conditions become stable.

The cost of constructing irrigation wells depends on the diameter and depth of the well, the drilling process used, the nature of the material encountered in the well, the locality, the kind of casing, the length of casing perforated, and the time spent in developing and testing the well. Data on the average cost of putting down wells by the various methods and in different States are given, but they should be used only for estimating purposes because the exact cost of the well will be determined by the conditions existing at the time the contract is made.

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